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NEPHELINE SYENITE PEGMATITES, ROCKY BOY STOCK, BEARPAW MOUNTAINS, MONTANA

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ABSTRACT

Unusual nepheline syenite pegmatites, mineralogically resembling in part those of the Kola Peninsula, are found in a composite stock of Tertiary alkalic rocks in the Bearpaw Mountains, Montana. The pegmatites occur in the field as small segregation knots in nepheline syenite and as lens-shaped (compact or clefted) bodies, dikelets, and dikes in nepheline syenite or contiguous monzonites and shonkinites. The pegmatitic bodies are very numerous in an area of a few square miles.

Two partial chemical analyses of sanidine, and complete analyses of potash nepheline, lamprophyllite, and fibrous aegirite are presented with descriptions of the physical properties of these and associated minerals. An analysis is also included of a potash-barium rich nepheline syenite, interpreted to have given rise by fractionation to the pegmatitic magma.

The distribution and utilization of the rare constituents in the formation of the minerals in the pegmatites are discussed. The pegmatitic magma probably had a low volatile content, high concentration of rare constituents (Ti, Zr, Sr), and high initial temperature; and it probably crystallized rapidly at a shallow depth. These pegmatites are the first expression of the differentiation history of the nepheline syenites, and are followed by more volatile-rich pegmatites and complex veins.

INTRODUCTION

In the summers of 1937-39, during geological investigations of the Bearpaw Mountains of north-central Montana, the writer studied several unusual pegmatites in a stock of early Tertiary alkalic rocks. The minerals identified from these pegmatites are: sanidine, nepheline, sodalite, albite, biotite, aegirite, melanite, stilpnomelane, eudialyte, catapleiite, elpidite, lamprophyllite, sphene, brookite, zircon, smoky quartz, calcite, pyrite and galena. Of these minerals, albite, zircon, brookite, stilpnomelane, and quartz are attached to walls of small solution cavities in the pegmatites.

Some of the igneous rocks of the mountains have been described by Weed and Pirsson (1896), and a brief summary of the general petrology was prepared by the writer and incorporated in a recent paper by E. S. Larsen (1940).

ROCKY BOY STOCK

Only the largest and most complex stock in the mountains contains the pegmatites described in this paper. Because of its location in the Rocky Boy's Indian Reservation, it has been named the Rocky Boy stock, and its location is shown in Fig. 1. The stock occupies about 12 square miles, has an exposed vertical relief of about 2200 feet, and a maximum elevation of about 6430 feet.

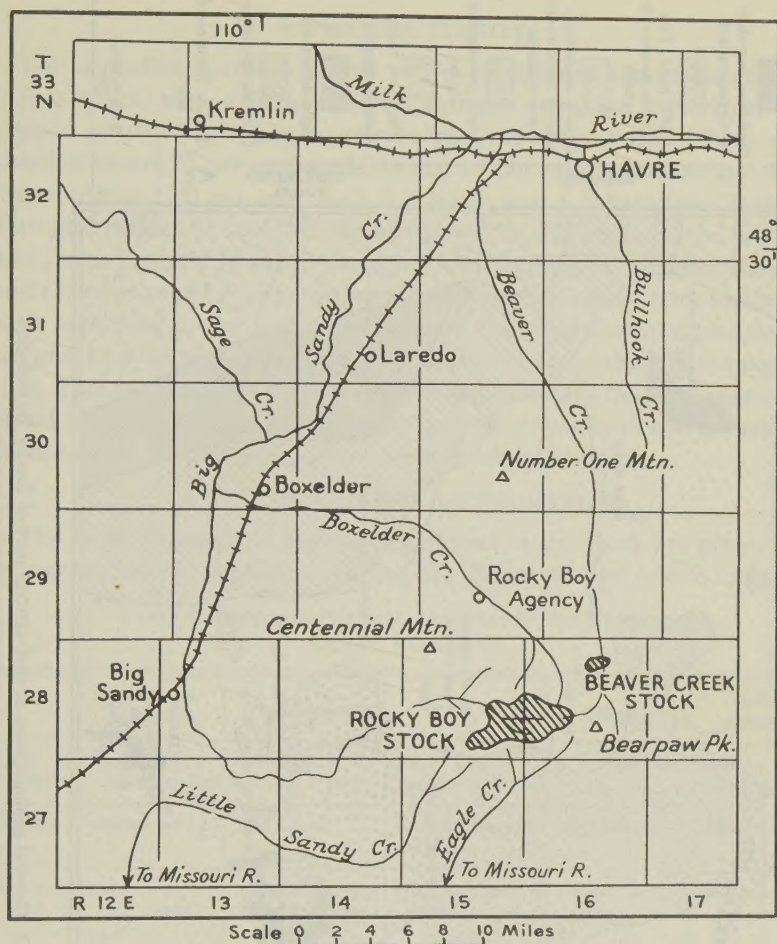


FIG. 1. Index map of a part of north-central Montana showing location of the Rocky Boy and Beaver Creek stocks.

Pyroxenites, shonkinites and syenites, nepheline or pseudoleucite shonkinites and syenites, monzonites, and pegmatite-bearing nepheline syenites make up most of the stock. The areal relations of these rocks, and the location of several pegmatite localities described in the text are shown in Fig. 2, a map of the eastern part of the stock.

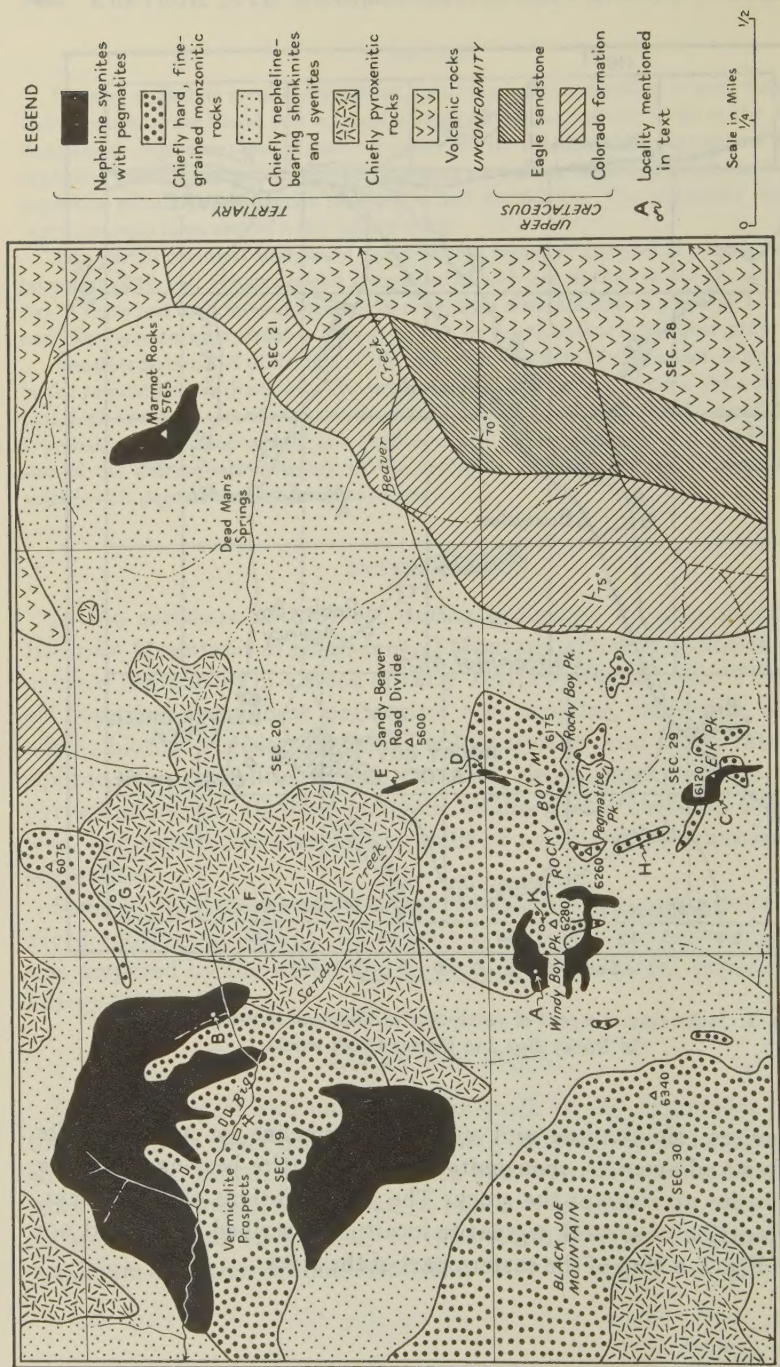


FIG. 2. General geologic map of east-central part of Rocky Boy stock showing locations of pegmatites described in text.

NEPHELINE SYENITES

The nepheline syenites related to the pegmatites are coarse-grained, friable rocks, with a greasy luster, and are intrusive into dark, fine-grained monzonites. A large specimen from the summit of Elk Peak, composed of about 75 per cent sanidine and 13 per cent nepheline and sodalite, contains 12.0 per cent K_2O , 2.3 Na_2O , and 1.5 BaO (see Table 2). Two generations of sanidine are recognized in this rock: (1) an intratelluric, zoned, partly resorbed variety with an appreciable barium content; and (2) an unzoned variety with a much lower barium content, associated with nepheline in the groundmass. Both the nepheline and sanidine in the groundmass of the syenite are optically similar to those in the pegmatites. This relationship, and other evidence, indicates that the pegmatitic liquid fractionated from crystallizing nepheline syenite rich in potash and barium after the precipitation of the early zoned sanidine.

FIELD DESCRIPTION OF PEGMATITES

The nepheline-aegirite syenite pegmatites in the stock are present (1) as segregations in nepheline syenite, (2) as lens-shaped bodies in neph-

TABLE 1. PRINCIPAL PHYSICAL FEATURES OF THE NEPHELINE SYENITE PEGMATITES

	Segregation Pegmatites	Lens-shaped	Dikes	Dikelets	Aplite Dikelets
Size of exposure	Small knots to few square feet	Average, 1'×10' Largest, 2'×30'	Small, 3'×20' Large, 8'×200'	1" wide, few feet long	1" wide, several feet long
Contacts	Gradational	Well defined	Irregular but well defined	Well defined	Well defined
Host rocks	Only in nepheline syenite	In nepheline syenite or contiguous rocks	Not in nepheline syenite	Not in nepheline syenite	Only in nepheline syenite
Mineralogy	Simple* Aegirite largely prismatic Melanite and biotite common	Simple* or complex† Aegirite essentially fibrous Rare biotite near contact	Simple* Rare biotite and lamprophyllite	Simple* Biotite absent	Simple* Biotite absent
Alteration	Rare solution cavities with zircon	Aegirite locally to limonite Solution cavities with crystals of albite, zircon, etc.	Aegirite locally to limonite	Rare	None
Principal identifying features	Small size and coarse grain	Some clefted lenses Transverse aegirite and lamprophyllite	Coarse feldspar Euhedral nepheline	Small size Transverse aegirite	Small size Green color Hard, compact

* Simple: sanidine, nepheline, aegirite are essential; biotite and melanite may be present.

† Complex: above minerals and also many rare minerals described in text.

line syenite or in older rock, (3) as dikes and dikelets in rocks older than nepheline syenite, and (4) as aplitic dikelets in nepheline syenite. Of these the second type is the most complex. A great number of pegmatites are exposed within a few square miles, but they are characteristically small bodies. A summary of the principal features of these pegmatites is given in Table 1.

SEGREGATION PEGMATITES

Size and Distribution.

Pegmatitic segregations in nepheline syenite vary in size from mere shreds and knots to bodies as large as a few cubic feet. The contacts of the small pegmatites with parent rock are completely gradational.

These pegmatites are most numerous in the nepheline syenites on Rocky Boy Mountain, especially on the western side of Windy Boy Peak. In one small area (locality *A*, Fig. 2) more than 25 pegmatites were noted, with some of them so concentrated or interconnected that it is difficult to determine which is parent and which is pegmatite.

At least 10 pegmatites were observed on Elk Peak, and the largest of them, having an exposed surface area of about 1 square foot, is present at locality *C*. Small shreds and knots are numerous in the small intrusions on the saddle north of Elk Peak.

Segregation pegmatites are more numerous on the western and eastern edges of the intrusion of nepheline-sodalite syenite, north of Big Sandy Creek, than they are in the main part of the intrusion. Pegmatites are rare in the intrusion south of Big Sandy Creek and are absent in the altered intrusion at Marmot Rocks.

Composition.

In the unaltered and compact segregation pegmatites, the common minerals are glassy sanidine, nepheline, sodalite, biotite, prismatic and fibrous aegirite, and melanite. The proportion of sanidine to nepheline, which are the chief minerals, is variable, but the sanidine is more abundant, in some places making up 75 per cent of the pegmatite.

The dark minerals make up a few to 20 per cent of the pegmatites. Generally, if biotite is present in excess of a few per cent, the prismatic aegirite is more abundant than fibrous aegirite; if fibrous aegirite is very abundant in a pegmatite, prismatic aegirite is scarce. Of the two habits of aegirite, however, the prismatic is more characteristic of the segregation pegmatites.

Some pegmatites contain only one dark mineral, and in these that mineral is more abundant than in those containing more than one dark mineral. One pegmatite (locality *B*) contains prismatic aegirite, oriented

as shown in Fig. 3. Many small pegmatites in the saddle north of Elk Peak contain much melanite with very sparse aegirite, and no biotite.

Solution cavities are rare in the segregation pegmatites. A few were observed at locality C, in the only segregation pegmatites which contain zircon.

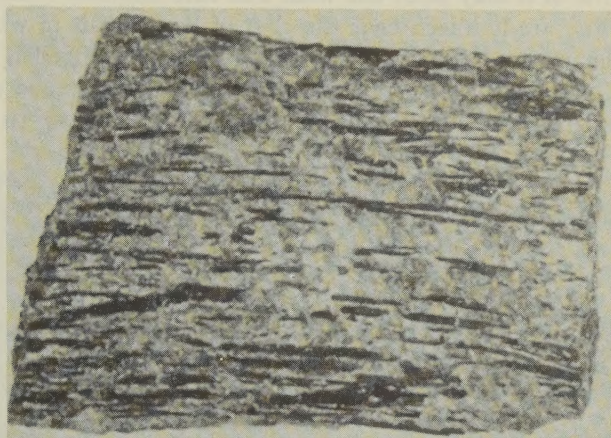


FIG. 3. Hand specimen of pegmatite showing oriented prismatic aegirite.

LENS-SHAPED PEGMATITES

General Statement.

The lens-shaped pegmatites are small but well defined, elongate bodies in nepheline syenite, or in older rocks near nepheline syenite. All of these pegmatites contain sanidine, nepheline, and aegirite as essential minerals, and a very few of them have a complex assemblage of minerals. Those pegmatites contained in nepheline syenite are commonly clefted and complex, and those not in nepheline syenite are compact and simple. There are probably all gradations between segregation and lens-shaped pegmatites in nepheline syenite.

Size, Form, and Structure.

The largest exposed pegmatite of this type is about 2 feet wide and 30 feet long. Most commonly they are less than one foot wide and less than 15 feet long. Undoubtedly their apparent size depends on the attitude of the pegmatite and the part of it which is exposed to erosion. Their complexity, however, is not dependent on their size, for some of the smallest ones are as complex in mineral composition as some of the largest.

The pegmatites are in fact individual tabular lenses. Vertical lenses are characteristic of most of the pegmatites in rocks other than nepheline syenite, whereas vertical lenses are rare in nepheline syenite at high

elevations. The lenses in the small intrusions of nepheline syenite have their long dimension parallel to the borders of the intrusion which encloses them.

The clefted lenses are those which have an elongate open space (cleft) parallel to the long dimension of the pegmatite. The cleft may be within the pegmatite or it may be at one wall. The rare minerals eudialyte and lamprophyllite are localized near the cleft of the deposit in which they occur. Large masses of fibrous aegirite are likewise controlled by nearness to the cleft. In all of the complex deposits, the two walls on either side of the cleft are smooth but uneven surfaces, and are up to one inch

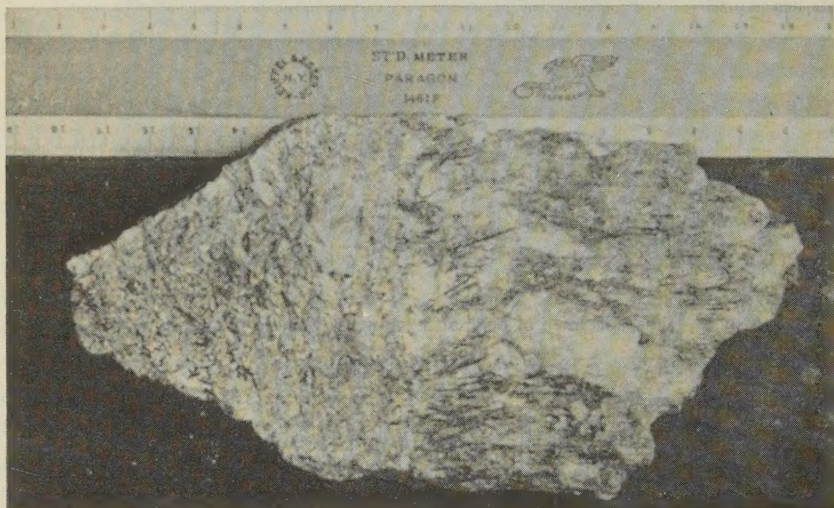


FIG. 4. Hand specimen (scale in cm.) showing well defined contact of lens-shaped pegmatite with nepheline syenite, and transverse aegirite.

apart as a maximum. The role that the cleft played during the history of the pegmatites is uncertain; but it is probable that the late residual solutions of the crystallizing pegmatite were in contact with the walls of the cleft, caused some solution, and probably soaked through the walls into the body of the pegmatite. The clefted lenses are most numerous on and near Pegmatite Peak above the elevation of 6100 feet.

The clefted and unclefted lenses have two structural features in common: (1) with one exception noted below the contacts with enclosing rock are well defined and (2) the fibers of aegirite and the cleavage fractures of sanidine are oriented in a direction normal to the contact. Both features are shown in Fig. 4. One pegmatite on the saddle southeast of the summit of Windy Boy Peak has an ill defined contact with a dike of pseudoleucite shonkinite. As shown in Fig. 5, both sanidine and aegirite have been introduced into the groundmass of the shonkinite.

A few pegmatites at the western edge of the nepheline-sodalite syenite north of Big Sandy Creek are clefted lenses exhibiting a special feature not observed elsewhere. The main mass of the pegmatite is enclosed in a shell a few inches thick of coarse-grained, tabular feldspar with a "trachytic" texture. The tablets are crowded, and are oriented parallel to the

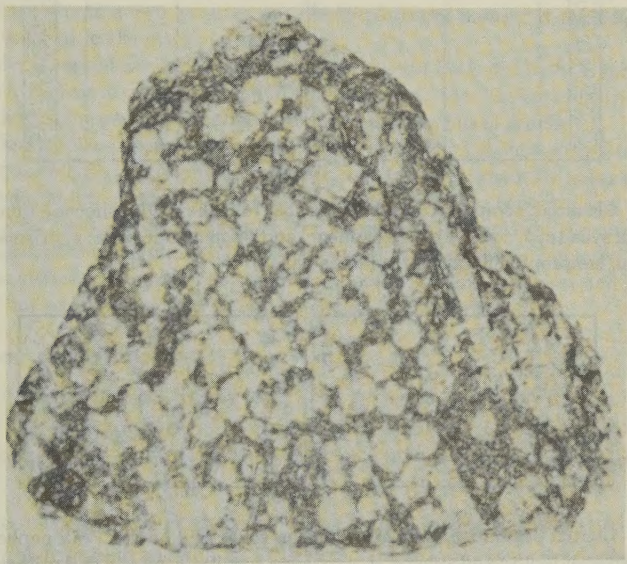


FIG. 5. Hand specimen of pseudoleucite shonkinite wall rock of a complex pegmatite showing introduced black prisms of aegirite and rectangular grains of sanidine.

well defined contact of the pegmatite. The shell is gradational into the main part of the pegmatite.

Distribution.

More than 50 lens-shaped pegmatites were noted in a few square miles of the eastern part of the Rocky Boy stock. No pegmatites have been observed in the western part of the stock, or in the country rock beyond the border of the stock. Those in nepheline syenite have their greatest concentration on the summit and upper slopes of Rocky Boy Mountain, and those not in nepheline syenite are randomly distributed in the older rocks of the stock shown in Fig. 2. Nearness to a body of nepheline syenite increases the number of pegmatites in the older rocks of the stock, and this is well illustrated at the localities of Dead Man's Springs (pegmatite lenses in pseudoleucite shonkinite), and the northern slopes of Windy Boy Peak (pegmatites in monzonite).

The lens-shaped pegmatites have been observed between elevations of 4700 feet to 6300 feet. The most complex pegmatites are on the summit of Rocky Boy Mountain between elevations of 6000 and 6200 feet. Some of these, on the summit of Pegmatite Peak, extend continuously from nepheline syenite into contiguous, hard, jointed monzonite.

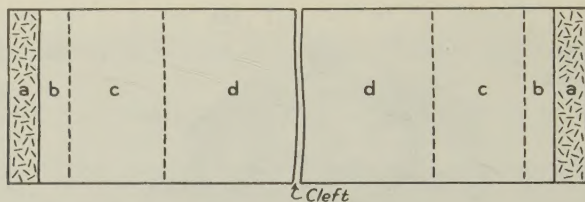


FIG. 6. Idealized, complex, clefted pegmatite (14 inches wide) showing mineral zoning: *a*, nepheline syenite; *b*, zone of biotite, sphene, and prismatic aegirite; *c*, prismatic aegirite; *d*, eudialyte, lamprophyllite and prismatic aegirite.

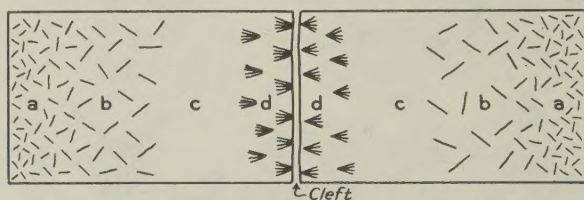


FIG. 7. Clefted pegmatite (8 inches wide) on south end of Elk Peak nepheline syenite showing zoning of biotite and sphene: *a*, nepheline syenite; *b*, biotite and prismatic aegirite; *c*, prismatic aegirite; *d*, acicular sphene replacing sanidine.

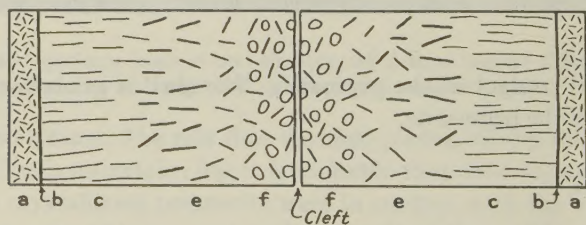


FIG. 8. Idealized, zoned, clefted pegmatite (2 feet wide) free of biotite and sphene: *a*, nepheline syenite; *b*, well defined contact; *c*, transverse aegirite fibers and lamprophyllite laths; *e* bladed lamprophyllite with fibrous and prismatic aegirite; *f*, coarse eudialyte with bladed lamprophyllite and prismatic aegirite.

Composition.

Most of the pegmatites contain only sanidine, nepheline, and aegirite, and a few of the most complex ones contain all the identified minerals. Although in some pegmatites the rare minerals are abundant, they repre-

sent a small percentage of the total mineral composition. The distribution and relations of the minerals are included in a later section on descriptive mineralogy. The spatial relations of some of the unusual minerals in the complex pegmatites, in part schematically shown in Figs. 6, 7, 8 can be briefly summarized in the statements below.

1. In the observed pegmatites which contain biotite, sphene, eudialyte, and lamprophyllite, the first two minerals are restricted to the borders of the pegmatite, and the last two to the margins of the cleft.
2. In the observed pegmatite masses which contain both biotite and sphene, but in which eudialyte and lamprophyllite are absent, the biotite is restricted to the borders of the pegmatite but the sphene to the margins of the cleft.
3. In the slab-like pegmatites in monzonite at the summit of Pegmatite Peak, the sanidine, eudialyte, lamprophyllite, aegirite, and to a less extent the sphene, have been introduced into the monzonite up to 6 inches beyond the contact.
4. Melanite, which is so common in the segregation pegmatites, is a very rare constituent in the complex lens-shaped pegmatites. Melanite is common, however, in those clefted lenses which do not contain biotite, sphene, eudialyte and lamprophyllite, but which do contain an abundance of fibrous aegirite.

Alterations and Veins.

In many pegmatites, local areas are present in which all the nepheline and much of the aegirite is completely destroyed. Irregular cavities with soft limonitic dirt, and tiny crystals of albite perched on the walls now remain.

On the summit of Pegmatite Peak, a second kind of alteration has formed in a few pegmatites in addition to the one described above. Some unknown minerals, probably eudialyte and aegirite, have been destroyed, and the resulting solution cavities are coated with pyramidal crystals of zircon and compact rosettes of stilpnomelane.

In the same altered pegmatites on Pegmatite Peak, a few tiny veinlets composed essentially of albite have formed in fractures in the rock. Brookite, elpidite (?), and a few unidentified minerals are also present in these veinlets. The veinlets are insignificant, as are the alterations, in consideration of the total volume of the pegmatites; but nevertheless, they represent a recognized process of mineralization that may well have been more active if certain other conditions existed during the late history of pegmatite formation.

Sulfides and Carbonates.

A few of the complex pegmatites on Rocky Boy Mountain contain rare specks of sulfides (pyrite and galena) which are entirely enclosed in halos of altered feldspar up to $\frac{1}{2}$ inch in diameter. Sulfides have not been observed in veins in these pegmatites. Microscopic quantities of calcite and ankerite have been observed on the walls of a few solution cavities.

PEGMATITE DIKES

General Statement.

Four pegmatite dikes of nepheline syenite have been observed in the stock, one in monzonite, one in nepheline shonkinite, and two in biotite pyroxenite. Except for a very rare lamprophyllite, they do not contain the unusual minerals found in the lens-shaped pegmatites. Sanidine, nepheline, and fibrous aegirite are the essential minerals of the dikes, and prismatic aegirite, biotite, and melanite are locally present.

Dike in Monzonite.

A dike 8 feet thick is exposed for about 100 feet in a gully north of Pegmatite Peak (locality *D*). It strikes N.W. and dips about 25 degrees N.E. At the ill-defined footwall contact, the dike is composed of fine-grained banded nepheline syenite. Separating this from the main, feldspar-rich part of the dike is an intermediate zone about one foot thick composed of coarse-grained nepheline syenite. The upper part of the dike is not exposed. Some differences between the main and intermediate parts of the dike are listed below:

1. The sanidine of the intermediate zone is glassy, whereas that of the main part is dull, green, altered, and up to a few inches in size across cleavages.
2. The nepheline is euhedral and much more abundant in the intermediate part.
3. Biotite and aegirite are abundant in the intermediate part, and the former is absent, the latter rare, in the main part.
4. Fibrous lamprophyllite is sparse in the intermediate part, and absent in the main part.

Dike in Nepheline Shonkinite.

A pegmatite dike is exposed for a few hundred feet at locality *E*. The dike is 6 feet wide, strikes N. 30 E. and dips about 25 degrees S.E. Some cleavage faces of sanidine in this pegmatite measure up to 8 inches across.

Dikes in Pyroxenite.

Two dikes of aegirite-rich pegmatite have been observed at localities *F* and *G*. They are composed essentially of altered and glassy sanidine, altered, euhedral nepheline, and abundant fibrous aegirite.

PEGMATITIC DIKELETS

Individual or groups of tiny dikelets, rarely more than one inch thick, have been observed in rocks older than and contiguous with nepheline syenite. They probably represent pegmatitic liquid injected along joint cracks. At locality *H*, a large massive outcrop of poikilitic monzonite has three well defined set of joints, and most of these joints contain the dikelets of nepheline-aegirite syenite pegmatite.

APLITIC SYENITE

A few thin, green dikelets in nepheline syenite, are exposed for several feet, and are hard and unaltered. In thin section, the rock of these dikelets is seen to be composed of very fine-grained sanidine, nepheline, and aegirite. The aegirite is proportionately more abundant here than in the host rock, or in pegmatites. Perhaps these green dikelets represent an aplitic phase of the pegmatites.

DESCRIPTIVE MINERALOGY

SANIDINE

General Description.

Sanidine is the most abundant mineral and makes up as much as 80 per cent of some pegmatites. Large cleavage faces up to 8 inches across are present in the large dikes. Glassy, transparent sanidine is very common, especially in the segregation pegmatites; but in most of the clefted lens-shaped pegmatites it has been hydrothermally altered.

One alteration, a pale green variety, is common in lens-shaped pegmatites rich in fibrous aegirite and in the main part of the pegmatite dike in monzonite. The green color is imparted to the sanidine by a great number of tiny, included crystals of aegirite, visible only under high magnification. In some feldspar, swarms or clusters of such aegirite crystals are clearly oriented along cleavage directions. There are all gradations in the size and abundance of the included aegirite, and presumably it is of replacement origin.

A second kind of alteration, a chalky white variety, is most common in the dike in shonkinite. Powdered grains are white and "dusty" in reflected light, apparently homogeneous in plane polarized light, and have a "splotchy" texture under crossed nicols. The texture suggests an incipient form of micropertthite. Integral parts of the same grain show twinning, with extinction angles differing as much as 10 degrees. This micropertthite (?) is perhaps hydrothermal.

Optical Properties and Chemical Composition.

The optical properties of glassy sanidines from the pegmatites are nearly the same. Refractive indices and optic angle vary slightly, however, beyond the controlled limits of accuracy of the determinative methods. The variations for several specimens are listed below.

Refractive Indices (Na)	Monoclinic
($\pm .001$)	(-)
$\alpha = 1.521-24$	$2V = 39-45^\circ$
$\beta = 1.526-29$	$r < v$, percep.
$\gamma = 1.527-30$	
Orientation (Universal stage): $Z = b$; and on (010), $X \wedge a = 9^\circ$	

The resorbed, zoned sanidine in some nepheline syenites differs distinctly optically from the unzoned sanidine of the pegmatites: β varies between 1.529–1.535 for the different zones; and 2V is nearly zero. The intermediate zones have the highest index.

In Table 2 are included partial analyses of two unzoned sanidines. One, (no. 2, Table 2) a soda-rich variety, has a β of 1.527 ($\text{Na} \pm .001$), and a 2V of $40^\circ (\pm 1^\circ)$; the second (no. 3, Table 2) a soda-poor variety, has a β of 1.528 and a 2V of 44° ,

TABLE 2. CHEMICAL ANALYSES

	1	2	3	4	5	6	7	8	9
SiO ₂	54.32			41.52	41.87	51.72	30.92	30.80	28.90
TiO ₂	0.51			none		1.32	31.73	31.26	27.70
Al ₂ O ₃	18.26			34.09	33.94	1.56	0.32	—	3.75
Fe ₂ O ₃	3.76			0.79	0.70	26.14	0.97	0.37	0.95
FeO	2.36					2.38	2.90	3.16	2.07
MnO	0.03					0.21	2.01	3.21	2.72
MgO	0.98					1.41	0.31	0.53	2.38
CaO	1.68			0.06	0.47	2.56	1.68	1.20	1.9
Na ₂ O	2.36	3.82	0.95	15.76	15.03	11.28	10.64	12.70	10.30
K ₂ O	12.04	11.82	14.83	6.85	6.68	0.34	0.99	—	0.60
BaO	1.46	0.26		0.03			1.12	1.09	1.8
SrO	n.d.			none			14.66	14.49	14.4
ZrO ₂	n.d.					0.24	—	—	—
P ₂ O ₅	0.22						—	—	—
F	n.d.						1.71	1.65	—
H ₂ O+	0.94			0.55		0.50	1.07	0.39	1.00
Total	98.92			99.65		99.66	101.03	100.85	99.47
O = F ₂							— .86	— .83	
							100.17	100.02	

1. Nepheline syenite (Q0₄), Elk Peak, Rocky Boy stock.
2. Sanidine, segregation pegmatite, Pegmatite Peak.
3. Sanidine (potash-rich), pegmatite dike in shonkinite.
4. Nepheline, complex pegmatite, Pegmatite Peak.
5. Nepheline, Greenland (Bøggild, 1905).
6. Fibrous aegirite, pegmatite dike in shonkinite. F. A. Gonyer, *analyst*.
7. Lamprophyllite, complex pegmatite, Pegmatite Peak. F. A. Gonyer, *analyst*.
8. Lamprophyllite, Kola Peninsula, Russia (Fersman, 1928, p. 121).
9. Molengraaffite, Transvaal, S. Africa (Brouwer, 1910). CaO, BaO, and SrO by H. C. G. Vincent (Tilley, 1938).

The variation of refractive index is probably a reflection of the barium content of the sanidine; whereas the 2V may be largely controlled by the physical conditions of crystallization.

NEPHELINE

General Description.

Nepheline is common, but makes up less than 30 per cent of any pegmatite. Euhedral outlines of hexagonal crystals are generally well preserved in the dikes, and the largest crystal observed is about 2 inches across the base. The largest single mass of nepheline observed in a complex pegmatite is about 4 inches in diameter.

Contact surfaces between nepheline and sanidine are most favorable for early replacement minerals, and, with few exceptions, the sanidine tends to be selectively replaced. Rarely, the replacement has been so complete that grains of slightly altered nepheline are imbedded in a mass of the replacing mineral (Figs. 9, 10).

The principal unidentified alteration product is a substance flesh-pink to red in color which encloses irregular cores of unaltered nepheline. Under high magnification it is sub-fibrous, and contains small unidentified inclusions of a metallic mineral and a reddish, translucent mineral. The composite refractive index of the alteration product is about 1.55, and its optical character indeterminate. Some grains appear to be biaxial (+) with a $2V$ of about 55° .

Yellowish, powdery halloysite is another alteration product and is most abundant in the syenite on Elk Peak.

Optical Properties and Chemical Composition.

The refractive indices of several samples of nepheline are variable: $\omega = 1.544\text{--}51$; $\epsilon = 1.539\text{--}45$. No systematic variation was observed in the pegmatites. The mineral is uniaxial (—).

In Table 2 is included an analysis (no. 4) of nepheline from a complex pegmatite. The sample was free of aegirite and lamprophyllite, and contained a fraction of one per cent of sodalite. The refractive indices, higher than those for common nepheline, are: $\omega_{Na} = 1.543$; $\epsilon_{Na} = 1.539 (\pm .001)$.

The high content of K_2O , Fe_2O_3 , and the low CaO are unusual for nepheline and are comparable to an analysis of nepheline from Greenland (no. 5, Table 2). The analyzed nepheline from the Bearpaw Mountains has a soda-potash ratio of 2.5:1, whereas most analyses of nepheline have a soda-potash ratio of from 4:1 to 5:1.

Bowen (1936) has described a nepheline containing about 11 per cent K_2O and has demonstrated that potash-rich nephelines are associated only with potash-rich rocks. Bannister's (1931) experimental data suggest that an increase in K_2O in nepheline commonly increases both the refringence and cell volume. The low percentage of BaO excludes the possibility of a control of refractive index by barium content, as is the suggestion for sanidine.

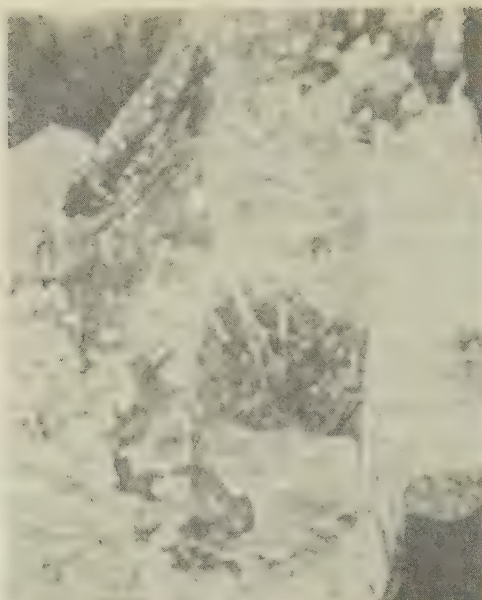


FIG. 9. Hand specimen from pegmatite dike in shonkinite showing fibrous aegirite (black), euhedral nepheline (gray), and sanidine (light).

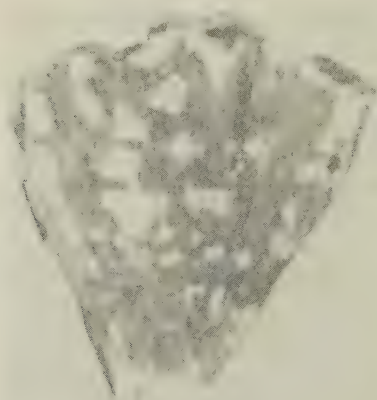


FIG. 10. Hand specimen of botryoidal mass of fibrous aegirite including grains of altered nepheline.

SODALITE

Sodalite is a common associate of fresh nepheline, and in some specimens is in graphic intergrowth with it. Sodalite is more abundant in the segregation pegmatites than in the host nepheline syenite. The mineral is isotropic and weathers to a bluish-white, amorphous substance having n near 1.427.

BIOTITE

Black biotite is an essential, though not abundant, mineral in the nepheline syenites and segregations and is present in the marginal parts of some lens-shaped pegmatites. The mineral makes up less than 5 per cent of any rock. It is coarser in the pegmatites, where it also has a higher refractive index. At locality *A*, some biotite books measure one inch across the base and two inches along the prism edge.

The mean refractive index on the cleavage flakes varies from 1.67 to 1.73; the highest values being restricted to long, thin, laths of biotite intimately associated with fibrous aegirite and lamprophyllite in the dike in monzonite. The biotite with lower refractive index is uniaxial (—); and some with high refractive index is biaxial (—), with $2V$ up to 25° . The biotite may be the variety lepidomelane.

Fersman (1937) has shown that an increase in the state of oxidation of iron is probably responsible for the increase in refractive index of lepidomelane from the Kola Peninsula. This oxidation, for the biotite in the pegmatite dike, could have been effected during the hydrothermal formation of fibrous aegirite.

GARNET (Melanite)

Garnet is most abundant in those segregation pegmatites which contain coarse biotite, but in which prismatic aegirite is scarce. None has been observed in the complex lens-shaped bodies which contain eudialyte, lamprophyllite, and prismatic aegirite. Many pegmatites on Rocky Boy Mountain contain abundant garnet, and in some of them fibrous aegirite is also abundant.

The garnet commonly is interstitial between sanidine and nepheline, molding around the grains of sanidine. In some places it is present along cracks in the feldspar and appears to replace it.

The garnet is rarely altered, is black, has a pitchy luster, breaks with conchoidal fracture, and has a brownish-red translucent color in strong light. Its specific gravity is 3.88 (Berman balance), and its n is about 1.95. A complex of interference faces characterizes its development, with striated contact surfaces intersecting in sharp ridges and valleys. The faces are possibly close to the dodecahedron, although that form cannot definitely be determined in any of the masses studied.

A qualitative test for titanium proved positive. The mineral may possibly be classified as a melanite, or titano-melanite, in accord with MacKowsky (1939), or may be related to schorlomite.

SPHENE

Sphene is not an abundant mineral in these pegmatites and has been observed in four relationships. One is typified by a segregation pegmatite at locality C. In this deposit, the sphene has a pseudo-prismatic habit, is restricted to grain boundaries of, or fractures in, sanidine. A second is typified by a small, clefted pegmatite at the south end of the Elk Peak intrusion, and is sketched ideally in Fig. 7. Sphene is confined to that part of the pegmatite on either side of the cleft as coarsely acicular masses replacing sanidine.

In a third association, in some slab-like complex pegmatites on Pegmatite Peak, sphene is confined to the border zone with biotite and prismatic aegirite (Fig. 6). In a fourth association at the same locality sphene has been introduced into monzonite for a few inches.

The sphene is honey-yellow, biaxial (+), has a small 2V, and $\beta = 1.94$.

AEGIRITE

Prismatic Aegirite.

Thin, black, non-terminated prisms of aegirite commonly up to one inch long, and rarely up to 4 inches in length, have been observed in many complex pegmatites. They are present in sanidine as randomly oriented, and in places, bent, curved, or broken prisms. The prismatic habit of aegirite is most conspicuous where the fibrous habit is scarce. Although there are all gradations in size of prisms, there appears to be a well defined break between the two habits in the same deposit, and commonly masses of the green, fibrous variety includes black prisms. Prismatic aegirite has a wide association of minerals in the pegmatites as shown in Figs. 6, 7, and 8.

Fibrous Aegirite.

In some deposits compact masses of green, fibrous aegirite include earlier formed minerals (Figs. 12, 13). Commonly the aegirite is developed between grain boundaries, or along cracks and cleavage faces of sanidine. Locally the aegirite is altered to limonite.

In small lens-shaped pegmatites the mineral is oriented with its long dimension normal to the wall of the deposit (Figs. 5, 8). Long laths of lamprophyllite are not uncommonly associated with fibrous aegirite in the pegmatite dikes and in the complex pegmatites.

Fibrous aegirite has been reported from Libby, Montana (Larsen and Pardee, 1913; and Goranson, 1927) and from Iron Hill, Colorado (Lar-

sen, report in press). Washington (1927) has made a survey of acmitic pyroxenes.

Optical Properties and Chemical Composition.

An analysis of fibrous aegirite from the dike in shonkinite is given in Table 2, no. 6. The material has 80 per cent of the acmite molecule, 10.3 per cent diopside, 4.7 per cent hedenbergite, and 5 per cent unassigned, composed principally of SiO_2 and Fe_2O_3 . The calculated chemical formula, in agreement with Berman's classification (1938) is expressed: $(\text{Na}, \text{Ca})_{.94}(\text{Fe}''', \text{Mg}, \text{Mn}, \text{Fe}'', \text{Al})_{1.05}\text{Si}_{1.95}\text{O}_6$; where $\text{Na}:\text{Ca}=8:1$, and $\text{Fe}''':(\text{Mg}, \text{Mn}, \text{Fe}'', \text{Al})=8:3$.

Many specimens of fibrous and prismatic aegirite have similar optical properties. Data for the analyzed material is given below:

Refractive indices ($\text{Na} \pm .001$)	Monoclinic
X (near c) = 1.757	Biaxial (—), $r > v$
Y ($= b$) = 1.786	$2V = 62^\circ$
Z = 1.797	Neg. elongation
Cleavage, (110) perfect	
Parting (?), (001)	

Small crystals studied in immersion liquids under high magnification afforded some opportunity for the determination of crystallographic data. By measuring the angles between prism edge and the traces of inclined terminal faces, the following crystal (or parting?) forms are indicated: $c\{001\}$; $u\{111\}$; $s\{\bar{1}11\}$; and $S\{311\}$.

EUDIALYTE

This complex sodium-zirconium silicate is present in a few of the complex and clefted pegmatites, and in them is coarse-grained and limited to the portions near the cleft (Fig. 8). It is intimately associated with bladed lamprophyllite. On Pegmatite Peak, eudialyte has been introduced into monzonite for about 6 inches. Within the pegmatites, eudialyte selectively replaces feldspar. Where the replacement has been complete, the mineral has a rose-red color, and where the replacement is incipient the mineral has a pink to flesh-pink color. In the few deposits in which it has formed it is an abundant mineral. The largest grains seen are about an inch in diameter.

No crystals of the mineral have been observed. The rose-red material is uniaxial (+), with $\epsilon = 1.606$, and $\omega = 1.600$. Grains in immersion media are pale yellow in transmitted light, and have a poorly developed basal cleavage.

A buff colored alteration product of eudialyte is, as seen in immersion

media, deeper yellow in transmitted light, sensibly isotropic, and has a slightly higher refractive index than the unaltered mineral.

LAMPROPHYLLITE

General Description.

This complex sodium-strontium titanosilicate has hitherto been reported only from the Kola Peninsula, Russia; although molengraaffite from the Transvaal, South Africa, is probably closely related to it. Coarse, platy books are associated with coarse eudialyte and prismatic aegirite, and long, thin laths are associated with fibrous aegirite. The largest plates are $2 \times \frac{1}{2}$ inches, and the longest laths are 4 inches. The mineral selectively replaces sanidine. No terminated crystals have been observed.

History.

Lamprophyllite is the name assigned by Hackman (1894) to the unidentified, brown, platy, astrophyllite-like mineral described by Ramsay (1890) from the Khibina Tundra of the Kola Peninsula. The present writer first discovered lamprophyllite in the Bearpaw pegmatites in 1937 and recognized its remarkable similarity to the Kola mineral. For comparison, lamprophyllite from Kola, molengraaffite from the Transvaal, and astrophyllite from southern Norway—all specimens from the Holden Collection at Harvard University—were studied microscopically. The Bearpaw and Kola lamprophyllite are almost identical in refringence, habit, and orientation. Molengraaffite has the same orientation and habit but lower refringence. Astrophyllite differs markedly in cleavage, orientation, and refringence (see Table 3).

Bohnstedt (1931) and Berman (1937) have suggested that molengraaffite is not a distinct species, as originally proposed by Brouwer (1911), but that it belongs in a series with lamprophyllite. Tilley (1938) has shown that the two minerals are chemically and optically related.

Gossner and Drexler (1935) concluded that x-ray studies on the Kola specimens indicate an orthorhombic symmetry. Their conclusions are not in accord with optical data obtained by the present writer and others on either Bearpaw or Kola specimens. Lamprophyllite has a fine, polysynthetic twinning parallel to the dominant (platy) cleavage; a fact which may have caused Gossner's erroneous conclusions. Laue photographs made by Professor C. S. Hurlbut, Jr., indicate either a monoclinic or triclinic symmetry.

Optical Properties and Chemical Composition.

An analysis of lamprophyllite from Pegmatite Peak is given in no. 7, Table 2, with a typical analysis of the Kola material (no. 8), and a par-

tial analysis of molengraaffite from the Transvaal (no. 9). The optical data are listed in Table 3, and orientation indicated in Fig. 11.

TABLE 3. COMPARISON OF OPTICAL DATA (SEVERAL SOURCES) OF TYPICAL LAMPROPHYLLITE WITH MOLENGRAAFFITE AND ASTROPHYLLITE

	Lamprophyllite, Bearpaw Mts. (Sp. gr. = 3.46)	Lamprophyllite, Kola (Sp. gr. = 3.5)	Molengraaffite (Sp. gr. = 3.54)	Astrophyllite (Sp. gr. = 3.4)
α	1.746	1.747	1.735	1.691
β	1.754	n.d.	1.747	1.705
γ	1.778	1.779	1.770	1.735
2V	40° (ca.)	23°-41°	28°	70° (ca.)
Character	(+)	(+)	(+)	(+)
Dispersion	$r > v$, str.	$r > v$, str.	$r > v$, str.	$r > v$, str.
Absorption	Z > X	Z > X	Z > X	Z > X
Pleochroism	deep to honey-yellow	deep to honey-yellow	brownish-yellow	deep orange to lemon-yellow
Cleavage*	(100)? platy, dom. (011)? good (010)? poor	(100) platy, dom. (011) good	(100) perf. (011) good	(010) perf. (001) imperf.
Orientation*	Y = or near a X = or near b $Z \wedge c = 5^\circ$	Y = or near a X = or near b $Z \wedge c = 7^\circ$	Y = or near a X = or near b $Z \wedge c = \text{small}$	Y near b Z near a
Symmetry	mon. or tric.?	mon. or tric.?	mon. or tric.?	mon. or tric.?

* See Fig. 11.

Conclusions.

Molengraaffite is probably structurally identical with lamprophyllite, and despite slight differences in chemical composition and optical properties may be considered a member of the lamprophyllite series. Lamprophyllite itself may be monoclinic, or possibly triclinic.

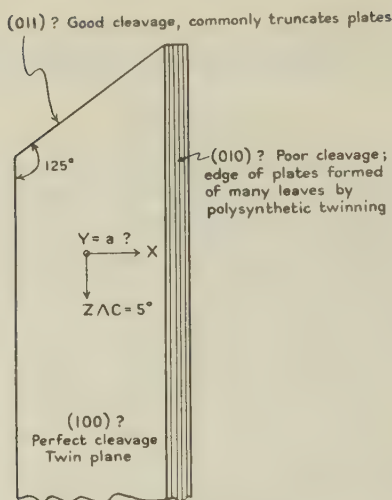


FIG. 11. Sketch showing relation of cleavages to optical orientation of lamprophyllite.

CATAPLEIITE

In a small part of some altered complex pegmatites on the summit of Pegmatite Peak, the writer observed a few granular aggregates of altered material in association with relatively fresh feldspar, nepheline, lamprophyllite, and prismatic aegirite. The alteration, probably derived from eudialyte, is composed of compact grains of glassy, twinned and untwinned catapleiite, mixed in a matrix of brown colored carbonate. The optical data of the catapleiite are listed below:

Refractive Indices ($\pm .002$)

$$\alpha = 1.590$$

$$\beta = 1.592$$

$$\gamma = 1.623$$

Twinned, both uniaxial (+) and biaxial (+) with very small $2V$.

Gelatinizes in HCl

Cleavage: poorly developed pyramidal. The twin law is not known. It is likely that this mineral is a hydrous alteration product of eudialyte.

ALBITE

Albite is commonly present as well formed tablets attached to the walls of solution cavities in altered pegmatites. The largest crystals are less than one inch long, and are best developed in the altered pegmatites on the summit of Pegmatite Peak.

BROOKITE

In one place tiny crystals of brookite are imbedded in a thin veinlet of

albite, but these crystals are not observed in the cavities. The crystals have the apparent shape of hexagonal bipyramids but are actually a combination of the forms $m\{110\}$ and $e\{122\}$ of the orthorhombic system.

ZIRCON

Zircon has been observed in two localities. In one locality it is intimately associated with stilpnomelane and smoky quartz. In a second, a large segregation pegmatite on Elk Peak (locality C), small solution cavities are coated with tiny pyramidal crystals of green zircon, with $\omega = 1.94$.

STILPNOMELANE

In an altered pegmatite on the summit of Pegmatite Peak, larger cavities are coated with rust-covered pyramidal crystals of zircon, and these are coated with compact rosettes of stilpnomelane. Tiny prisms of smoky quartz are attached to surfaces of the rosettes. Small flakes of stilpnomelane have also been observed to replace or to be attached to prisms of aegirite. In these altered areas, which are adjacent or contiguous to cavities containing albite, the eudialyte, some aegirite and some lamprophyllite have been destroyed.

In habit, the stilpnomelane resembles chlorite. The mineral is yellowish-brown to red, has a very high birefringence, is uniaxial (—) with ω about 1.78. The mineral has a strong absorption with $\omega > \epsilon$.

ELPIDITE (?)

A few silky tufts of a white, prismatic mineral of uncertain identification replace the albite of one veinlet on Pegmatite Peak. The optical properties of the mineral are listed below. The properties resemble those of elpidite, and the habit of the mineral resembles a fibrous zeolite.

Refractive Indices ($\pm .002$)	Orthorhombic
X = 1.563 = elongation	$2V = 90^\circ \pm 5^\circ$ (est.)
Y = 1.568	One perfect cleavage in zone of elongation.
Z = 1.573 = \perp to cleavage	

PARAGENESIS AND GEOCHEMISTRY

MINERAL ASSOCIATIONS

The precise order of formation of every mineral in the pegmatites cannot be determined with certainty; but, as shown in the paragenetic chart (Fig. 12) and in Table 4, age relations of group associations are more reliable.

TABLE 4. GROUP MINERAL ASSOCIATIONS AND THEIR RELATIVE AGES

Age groups	Minerals	Origin
1	Sanidine, nepheline, biotite	Magmatic
2	Biotite, prismatic aegirite, melanite, sphene	Transitional
3	Prismatic aegirite, eudialyte, lamprophyllite	Replacement
4	Lamprophyllite, fibrous aegirite	
5	Fibrous aegirite	Hydrothermal
6	Catapleiite	
7	Zircon, stilpnomelane, smoky quartz	
8	Albite, elpidite, brookite	
9	Pyrite, galena	

Where no alterations have occurred the minerals precipitated in the magmatic stage now form a solid, and compact rock. The compactness of the rock was maintained during the replacement stage of mineralization although some movement of materials was effected. In the hydrothermal stage, however, compactness was destroyed through solution of nepheline, eudialyte, and aegirite.

TEMPERATURE AND DEPTH OF FORMATION

The experimental data available in the literature concerning the behavior of twinned catapleiite, smoky quartz, and brookite may serve to indicate that the hydrothermal stage of mineralization existed at a temperature over 200° C. These minerals are confined to those deposits at the highest elevation (about 6300 feet). From a knowledge of the petrological relations in the Bearpaw Mountains, the depth of sedimentary and volcanic cover existing at the time of intrusion of these alkalic syenites is interpreted to have been at least 3000 feet, and may have been as much as 7000 feet.

At shallow depth, the rate of fall in temperature of the implaced magma may have been rapid, although the initial temperature was high. The writer believes that the coarseness of grain for these syenitic rocks is an inherent character, and that crystallization as well as eruption were rapid phenomena.

RARE CONSTITUENTS

As noted earlier in this paper, a potash and barium-rich (but soda-poor) syenitic magma gave rise, by fractionation, to a later (pegmatitic) syenitic magma not so rich in potash and barium, but much richer in soda. More barium was contained in the early magma than in the later one, whereas strontium, titanium, and zirconium became progressively more concentrated in the later magma. The affinity of these four rare elements for alkalic rocks has been widely recognized in the geological literature, and the close affinity of potash and barium is well supported in these studies.

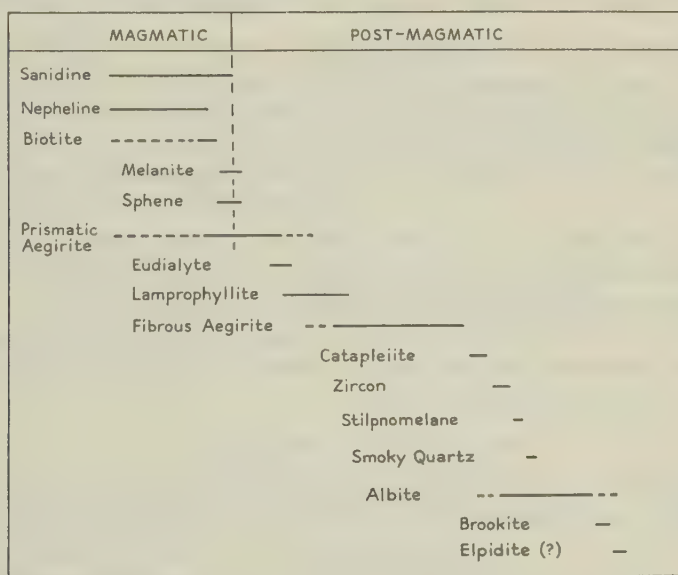


FIG. 12. Paragenetic chart of nepheline-aegirite syenite pegmatites.

Chemical analyses and optical data strongly suggest that most of the barium in the nepheline syenites and pegmatites mentioned in this paper is in the sanidine, and that more barium can be taken into solid solution with potash at the higher temperatures of crystallization. In the discontinuously zoned sanidine, refractive indices indicate that the intermediate zones of that mineral, not the cores, are richest in barium. Since the peripheral zones have about the same refractive indices as does unzoned, pegmatitic, soda-rich sanidine, perhaps 0.26 BaO (Table 2) may be considered as near the low limit of the barium content of the sanidine in

these syenites. No data are available as a control of the upper limit, but at least a few per cent BaO is an acceptable value.

Strontium, titanium, and zirconium have an unequal distribution in minerals of the pegmatites, as shown in Table 5.

TABLE 5. DISTRIBUTION OF STRONTIUM, TITANIUM, AND ZIRCONIUM
IN SIMPLE AND COMPLEX PEGMATITES

	Simple Pegmatites	Complex Pegmatites
Strontium	Aegirite	Lamprophyllite
Titanium	Melanite, aegirite	Sphene, lamprophyllite, and brookite
Zirconium	Aegirite	Eudialyte, catapleiite, zircon, and elpidite

The amount of titanium and zirconium shown in the analyzed fibrous aegirite from the pegmatitic dike is not necessarily a measure of the amounts of those elements in fibrous or prismatic aegirite from the simple or complex pegmatites. There are, however, no remarkable differences in composition of the aegirites for their optical properties are similar. No data are available as to the relative amounts of the rare constituents in the aegirite of the simple pegmatites, in contrast to that of the complex pegmatites, which represent a magma rich in those constituents. The MnO content of lamprophyllite and aegirite is noteworthy.

Two kinds of utilization of the rare constituents have been recognized in these pegmatites, and they are here named (1) distributive utilization, and (2) repetitive utilization.

DISTRIBUTIVE UTILIZATION

Distributive utilization is defined as the precipitation of a given constituent in more than one mineral of the same pegmatite, although the minerals containing that constituent are not necessarily contemporaneous in origin. The concept is well illustrated by those complex pegmatites on the summit of Pegmatite Peak in which titanium is contained in the minerals sphene, lamprophyllite, brookite, and aegirite; and zirconium in the minerals eudialyte, catapleiite, zircon, etc.

REPETITIVE UTILIZATION

The concept of repetitive utilization is suggested by those deposits in which some minerals (nepheline, eudialyte, aegirite) are chemically attacked or destroyed, and their constituents made available for the precipitation of stable, secondary minerals, either in place, or by transportation to another site. The reconstituted minerals may themselves be attacked under still later conditions, and robbed of certain constituents so that still younger minerals may be formed. The writer is of the opinion

that the formation of catapleiite, zircon, stilpnomelane, elpidite, brookite, albite, and smoky quartz are clear examples of repetitive utilization.

The insignificant volume of the secondary minerals resulting from this process, with respect to the volume of the unaltered pegmatites, is some indication of the scarcity of a fluid volatile in these syenitic magmas. A greater array of hydrothermal minerals would have been present in these pegmatites had there been a greater quantity of the same dissolving agent. Perhaps in the now-eroded rocks of a higher elevation in the stock, veins of reconstituted minerals were more common than they are in the now-exposed rocks on Pegmatite Peak. The process of repetitive utilization is well supported, and can well be applied to the great array of hydrothermal minerals associated with a younger set of pegmatites mentioned below.

OTHER DEPOSITS

In the area around the Vermiculite Prospects on Big Sandy Creek (Fig. 2) are exposed numerous pegmatites and veins which will be subjects of a forthcoming paper. For the purposes of general comparison, however, a brief list of them is here presented:

1. Biotite-acmite syenite pegmatites.
2. Biotite syenite pegmatites, with younger complex veins composed of a great array of silicates, oxides, sulfides, carbonates, and other compounds.
3. One vein composed essentially of calcite and apatite, graphically intergrown, and containing fluorite and pyrite.
4. Veins composed essentially of albite and brookite.
5. Veins composed essentially of smoky quartz, with sulfides and carbonates.

The deposits listed above are all related to the igneous activity in the Rocky Boy stock; and there is positive evidence that two deposits (1 and 2, above) are both younger than the pegmatites described in this paper.

CONCLUSIONS

The nepheline-aegirite syenite pegmatites in the Rocky Boy stock of the Bearpaw Mountains more nearly resemble the unusual pegmatites of the Kola Peninsula in northern Russia than those of any other described region. Some resemblance is noted, in part, to classic localities such as southern Greenland, southern Norway, Magnet Cove, Arkansas, and others. It is likely that the origin of the pegmatitic and parental alkalic magmas of these different regions is similar. In the Bearpaw deposits the mineralization has occurred on a less grandiose scale, but the same processes of mineralization are noted here. Initial compositions of the pegmatitic magma, rate of fall in temperature after its emplacement, and amount of active volatile residue are all variable factors governing the complexity of the mineral assemblage in these pegmatites.

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DISTRIBUTION OF MINOR CHEMICAL ELEMENTS IN TERTIARY DIKE ROCKS OF THE FRONT RANGE, COLORADO

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ABSTRACT

Qualitative and quantitative spectrographic analyses determining the minor chemical constituents in a number of Colorado Front Range Tertiary dike rocks and their constituent minerals revealed some interesting relationships. The rocks analyzed were mainly monzonites and latites. The rock analyses (qualitative) showed some regional differences in the number and quantity of minor elements present. Slight variations with rock type also were found. Elements of special significance in the rock analyses are: Pb, Ni, Co, Sc, Cr, V, and La.

Analyses of plagioclase, biotite, groundmass, and magnetic concentrate samples (both qualitative and quantitative) showed systematic differences in the number and quantity of minor elements in each of the minerals. A few significant elements in the mineral analyses are: Sc, Y, La, Ce, Nd, Ti, V, Cr, Mn, and Co.

Comparison of analytical results obtained for the Tertiary dike rocks with those obtained for other Front Range igneous rocks of pre-Cambrian and Tertiary ages (not dikes) revealed definite points of difference. It is the author's firm belief that the spectrographic method, when properly applied, will prove a definite aid in correlation problems involving igneous rocks anywhere.

INTRODUCTION

The results here recorded represent a part of the work done in 1940 at the Massachusetts Institute of Technology as partial fulfillment of the requirements for the degree of Doctor of Philosophy in Geology. The spectroscopic distribution of minor chemical elements in the igneous rocks and rock-forming minerals of the Jamestown district, Colorado, has been taken up by the author in detail in another paper. (Bray, 1942). This paper points out that each rock body considered is characterized by its set of special minor elements, which vary with rock type, age, and province.

The Colorado Front Range offers an ideal province for the application of the spectrographic method, not only to purely petrological problems, but to those of correlation as well. The Jamestown district, with its diversity of igneous rocks, was the logical locality for the petrological study, and the surrounding sections of the Front Range, with the Tertiary sequence of dike intrusions, was equally suitable for attack upon the correlation question. In this study qualitative spectrographic analyses were made of 9 different dike rocks and 18 mineral samples, as well as quantitative analyses of 13 mineral samples. Among the rocks analyzed are: hornblende, biotite and quartz monzonites, biotite latites, and limburgite. All but the latter are somewhat similar.

The research was done in the Cabot spectrographic laboratory in the department of Geology at the Massachusetts Institute of Technology. The specimens (except those furnished by Dr. T. S. Lovering) were collected in 1939. The writer desires to express his deep appreciation to Dr. W. H. Newhouse, of the Massachusetts Institute of Technology, for his suggestions during the course of the work, to Mr. R. F. Jarrell, for his competent instruction in spectroscopy, and to Professor T. S. Lovering of the University of Michigan, for his interest and cooperation, as well as for furnishing several very interesting specimens. Mr. Albert Jehle gave painstakingly of his time and energy in assisting with the laboratory work.

GEOLOGY AND PETROLOGY

The area under consideration is located in Clear Creek and Boulder Counties, near the northeast edge of the Front Range mineral belt of Colorado. The geology of the Front Range needs no detailed repetition, as it has been ably discussed by Ball (1908), by Lovering (1929) and by Fenneman (1905). The main country rock consists of an ancient pre-Cambrian complex of gneisses and schists, intruded by a series of pre-Cambrian granite batholiths. This entire assemblage was subjected to the forces of the Laramide Revolution, which resulted in fracturing, in-

trusion of a series of Tertiary stocks and dikes, and a period of valuable metallization.

Lovering and Goddard have published a geologic map of the Front Range mineral belt under the auspices of the United States Geological Survey (1938*b* and 1939). The only rocks of any concern here are those of the Tertiary group. The physical chemistry involved in the formation of these rocks has also been considered by Lovering and Goddard (1938*a*, pp. 59-67). As for the Tertiary igneous sequence in the Boulder County area, the author follows Goddard in his report on the Gold Hill district (1940). The sequence is as follows, beginning with the first rock intruded:

- Diabase dikes (oldest)
- Hornblende granodiorite stock and dikes
- Intermediate quartz monzonite porphyry stock and dikes
- Alaskite porphyry dikes
- Sodic granite-quartz monzonite porphyry stock and dikes
- Bostonite porphyry dikes
- Biotite monzonite and latite porphyries (also biotite latite intrusion breccia)
- Limburgite (youngest of series)

From this group of rocks, the author secured and analyzed specimens of the hornblende granodiorite, intermediate quartz monzonite porphyry, sodic granite-quartz monzonite porphyry, biotite monzonite and latite porphyries, biotite latite intrusion breccia, and limburgite. The granodiorite and sodic granite stocks were considered with the Jamestown rocks (Bray, *ibid.*). The petrology of the rocks here concerned is as follows:

Intermediate Quartz Monzonite Porphyry. (Sample No. 125-A. From a dike in the Jamestown district.) Megascopically this is a gray to yellowish rock containing a large number of hexagonal black biotite plates and less numerous glassy quartz phenocrysts disseminated in a groundmass of fine-grained quartz and feldspar (oligoclase-andesine and orthoclase), which is almost completely altered to sericite mica and clay minerals, yet showing former feldspar crystal boundaries. The phenocrysts are very fresh. Apatite is also present in the groundmass.

Biotite Monzonite. (Sample No. 125. From a dike in the Jamestown district.) This is a gray porphyritic rock with many fresh andesine phenocrysts, small plates of biotite, and altered hornblende needles, set in a dense, uniform groundmass composed of equal amounts of tiny oligoclase-andesine laths and anhedral orthoclase grains. Calcite is abundant in the groundmass. Fresh magnetite is a very abundant accessory. Sphene and apatite are minor constituents.

Hornblende Monzonite. (Sample No. 124TL33. From the Logan Mine, in the Gold Hill district, about 4 miles west of Boulder.) This sample was

donated by Dr. T. S. Lovering. The dike is a light gray rock containing numerous phenocrysts of clear, white, zoned oligoclase-andesine, fewer biotite plates, and a few former crystals of hornblende now completely

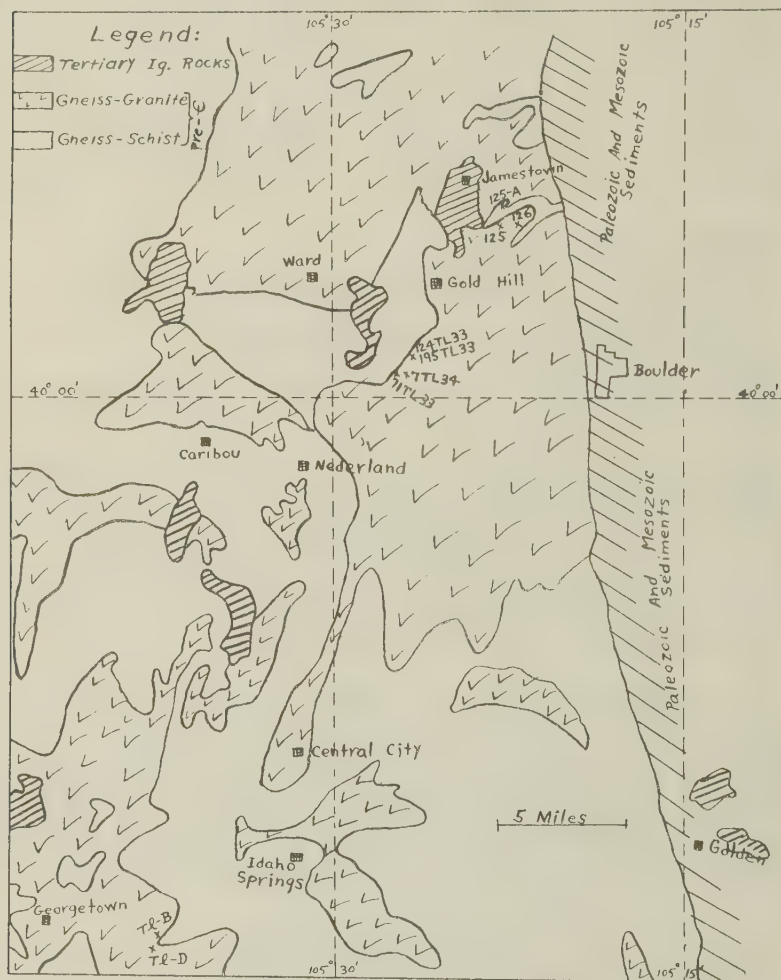


FIG. 1. Sketch Map—Location of Specimens.

altered to calcite. The groundmass is very dense and uniform, partly glassy, and composed of innumerable tiny andesine laths. Magnetite is abundant.

Biotite Latite Intrusion Breccia. (Sample 195TL33, donated by Dr. T. S. Lovering. From the Yellow Pine mine, Gold Hill district.) This sample is from the same dike as No. 124TL33. A light gray rock containing many phenocrysts of fresh, clear, quartz and altered plagioclase. Few biotite phenocrysts are present. Some potash feldspar and plagioclase crystals are unaltered. The groundmass contains small fragments of altered granite (?), is very fine-grained to glassy, and is crowded with minute shreds of quartz, feldspars, sericite, and clay minerals. Some quartz in the groundmass apparently was introduced. Abundant small grains of pyrite were apparently introduced by the tungsten-bearing solutions.

Biotite Latite. (Samples TL-B and TL-D, from dikes near the intersections of the 3 Chicago Creeks, about 6 miles southwest of Idaho Springs.) Gray, dense rocks, "spotted" by small black anhedral biotite plates. Flow lines are common. Small orthoclase and andesine phenocrysts are set in a very uniform groundmass of partially-devitrified glass containing numerous spherulites. The spherulites are often replaced by calcite. Accessories are magnetite, apatite, and zircon.

Limburgite. (Sample No. 7TL-34, donated by Dr. T. S. Lovering. From near Sugarloaf, about 5 miles west of Boulder.) A very dark, fine-grained dike rock composed of about 85 per cent augite and 10 per cent olivine (T. S. Lovering and E. N. Goddard, 1938*a*, p. 66).

Figure 1 is a sketch map of the area, showing the approximate locations of the samples analyzed.

ANALYTICAL METHODS

Space does not permit a detailed discussion of the methods used. The analyses were performed with a 21-foot, 30,000-line (per inch concave) grating spectrograph on a Wadsworth mounting. The cathode layer method of carbon-arc analysis was followed, with special techniques as outlined by the author in another paper (Bray, *ibid.*).

Great care was exercised in preparing and handling the samples. Mineral samples were carefully separated by hand. Qualitative analytical work was done by means of eye-estimation of the density of spectral lines. Quantitative analyses were performed by the internal-standard method, refined by use of iron step-sector calibrations and photometric density measurements. The results are reported in terms of oxides because oxides were used in preparing the standard mixtures. All analyses were done in duplicate, so each figure listed represents the mean of at least two separate determinations.

The symbols used to tabulate qualitative results are as follows:

VL—Very large	
L—Large	(Variations within one range are
M—Medium	expressed by means of plus
S—Small	and minus signs)
T—Trace	
VT—Very small trace	
N.D.—Not detected	
0—Not determined	

Absolute percentage figures cannot be assigned to these steps, and *symbols should be used only in comparisons involving a single element*. The spectrographic sensitivities of the various elements vary widely, so that a quantity designated as "large" for one might really be a smaller actual percentage than that for another element designated as "medium." It must also be borne in mind that when we speak of "large" amounts of the elements, we mean "large" *only in a spectroscopic sense*.

Qualitative analyses of minerals were run in a different manner from those of the rocks, so *the two sets of results are in no way to be compared*. Quantitative results are reported in percentages of oxides, except for elements that were not placed in the standard base mixtures for various reasons (unavailability, impurity, etc.). In these latter cases, the constituents are reported as " Δ log. E" figures, strictly quantitative and accurate. A higher positive " Δ log. E" value represents a larger percentage than a smaller positive value. Negative figures represent smaller percentages than positive figures. The " Δ log. E" values should be used *only in comparisons involving single elements in each mineral*.

The spectral range chosen did not contain sensitive lines for all elements desirable for this study. For instance, sensitive Li and B lines were lacking. In addition, lines present in this range for a number of desirable elements (such as Nb, Ga, Rb, and Cs) were either too diffuse, too near sensitive lines of major elements (thus being masked), or concealed by cyanogen lines. Old spectrographic analyses doubtlessly at times reported the presence of certain elements that were not actually present, due to confusion with other spectral lines in the same vicinity.

The results for the magnetic concentrates are not as sensitive as could be desired, as the samples had a tendency to hop from the electrode during the excitation process.

QUALITATIVE ANALYSES

Rocks

Table 1 lists qualitative analyses of 9 dike rocks. The minor elements of most common occurrence are Sr, Ba, Sc, Y, Ce, Ti, Zr, V, Cr, Mn, and

Co. Of these, Sr and Ba seem most abundant, although Mn, V, and Cr are present in appreciable quantities. Elements not detected in any of the samples are: Sb, As, Bi, Cd, Be, Ge, Au, Os, Ir, Pd, Pt.

TABLE 1. QUALITATIVE ANALYSES OF ROCK SAMPLES

Sample No.	Sr	Ba	Sc	Y	La	Ce	Nd	Ti	Zr	V	Cr	Mn	Co	Ni	Pb
125	VL	VL	VT	T	N.D.	T	T ⁺	L	VT	VL	M	L ⁺	VT	VT?	T
126	VL	VL	T	N.D.	S	VT	T ⁺	L	T ⁺	M	S	L	VT	N.D.	VT
71TL33*	VL	VL	N.D.	N.D.	N.D.	N.D.	N.D.	S	N.D.	L	S ⁺	L	N.D.	N.D.	VT
125-A	VL	VL	T	N.D.	N.D.	VT	T ⁺	L	T ⁺	M	S	L	VT	N.D.	N.D.
124TL33*	VL	VL	T	N.D.	N.D.	N.D.	VT	L	N.D.	M ⁺	T ⁺	L	N.D.	N.D.	N.D.
195TL33*	VL	VL	T	T	N.D.	T	N.D.	L	T	L	M ⁺	S	T	S	N.D.
TL-B	VL	VL ⁺	VT	N.D.	S	T	N.D.	M ⁺	T	M ⁻	S ⁻	L	N.D.	N.D.	N.D.
TL-D	VL	VL	VT	N.D.	S	N.D.	N.D.	M	N.D.	S	T	L ⁺	N.D.	N.D.	N.D.
7TL34*	VL	VL	S	VT	VT?	N.D.	N.D.	L	VT	M ⁺	VL	L	T	S	N.D.

125—Biotite monzonite (Jamestown)

126—Hornblende monzonite (Jamestown)

71TL33—Hornblende monzonite (Sugarloaf Mt.)

125-A—Quartz monzonite (Jamestown)

124TL33—Biotite latite (Logan Mine, Gold Hill)

195TL33—Biotite latite intrusion breccia (Gold Hill)

TL-B—Biotite latite (intersection of Chicago Creeks)

TL-D—Biotite latite (intersection of Chicago Creeks)

7TL34—Limburgite (near Sugarloaf, Boulder County)

* Samples donated by T. S. Lovering.

Not detected in any samples:

Sb, As, Bi, Cd, Be, Ge, Au, Os, Pd, Pt, Ag, Zn.

Explanation of Symbols:

N.D.—not detected

VT—very small trace

T—trace

S—small

M—medium

L—large

VL—very large

0—not determined

Several features of the analyses deserve special mention. First, Ag and Zn were not detected in any samples, and Pb is confined to the hornblende and biotite monzonites. The element Co is quite generally present, except in the biotite latite dike rocks. Ni, where present, occurs in those rocks where Co is most abundant. Sr and Ba are high in all of the rocks. Sc seems to be lowest in the "biotite rocks" (that is, the biotite monzonites and latites). The rare earth elements occur sporadically, with Ce most generally present. V is rather abundant in all samples, but tends to be lowest in the biotite latite dike rocks, and highest in the limburgite and intrusion breccia. An exactly similar relative distribution is shown by Cr. It is interesting to note several "pairs" of chemically-similar elements that seem to be distributed in parallel fashion in these rocks. Three such pairs are Sr-Ba, Ni-Co, and V-Cr. The same was found true for the pre-Cambrian and Tertiary granitic stocks of the Jamestown district (Bray, *ibid.*).

One point brought forcibly to attention by Table 1 is that the limburgite and intrusion breccia are so different from the other rocks concerned, especially as regards Ni, Co, and Cr, while being similar to each

other. Both rocks contain very many of the minor elements, some in quite large amounts. A significant fact brought out by Lovering and Goddard (1938, p. 66) is that both these rocks seem to be genetically related to the tungsten ores of this district, the limburgite being formed by remelting of basic crystal settlings as a consequence of explosive release of pressure exerted on the magma chamber. The released volatiles apparently deposited the tungsten ores (Lovering, 1940, pp. 142-143). A small trace of tungsten was found in the intrusion breccia.

Definite regional differences occur as well as the general differences in distribution of the minor elements already pointed out. For instance, Pb is confined to the Jamestown rocks, and (if we exclude the limburgite and intrusion breccia) V, Co, Cr, and Sc all tend to be highest in these same rocks. La, on the other hand, is highest in the Chicago Creek rocks. So there are definite regional differences as well as differences based on rock type. Important "index elements" (those which show these variations) are Pb, V, Co, Cr, Sc, and La. If these results are compared with qualitative analyses of the Jamestown stocks, it can be seen that the Tertiary group differs materially in a number of respects from the pre-Cambrian group (Bray, *ibid.*).

Minerals

The minerals analyzed qualitatively included plagioclases, biotites, magnetic concentrates, groundmasses and one hornblende. Results are tabulated in Tables 2 to 6. Each number in the tables indicates the rock sample from which each mineral was separated.

TABLE 2. QUALITATIVE ANALYSES OF PLAGIOCLASES

Sample No.	Sr	Ba	Nd	Ti	V	Cr	Mn	Ag
TL-B	M	L	VT	T	N.D.	VT	VT	N.D.
124TL33	VL	L	?	S ⁺	M	VT?	M ⁻	VT

Not detected in any samples: Sb, As, Be, Bi, B, Cd, Ce, Cs, Co, Ge, Au, Hf, In, Ir, La, Pb, Mo, Ni, Os, Pd, Pt, Sc, Sn, W, Y, Zn, Zr.

TABLE 3. QUALITATIVE ANALYSES OF GROUNDMASS SAMPLES

Sample No.	Sr	Ba	Sc	Y	La	Ce	Nd	Ti	V	Cr	Mn	Fe	Co	Yb
125	VL	VL	T	T	T	VT	T	L	L ⁻	T ⁺	M	L	N.D.	VT
71TL33	VL	VL	N.D.	?	N.D.	N.D.	N.D.	M	M	T	M	L	N.D.	VT
124TL33	VL	VL	T	T	N.D.	VT	T	L	L	S ⁺	M	L	VT	VT ⁺
TL-B	VL	VVL	VT	VT	T	T	VT	L	T	N.D.	L	L	N.D.	VT
TL-D	VL	VL	?	T	N.D.	VT	N.D.	M	T	N.D.	M	L	N.D.	VT ⁺

Not detected in any samples: Sb, As, Be, Bi, B, Cd, Cs, Ge, Au, In, Ir, Pb, Mo, Ni, Os, Pt, Ag, Sn, W, Zn, Zr

TABLE 4. QUALITATIVE ANALYSES OF BIOTITE

Sample No.	Sr	Ba	Sc	Nd	Ti	Zr	V	Cr	Mn
TL-D	T	VL ⁺	N.D.	VT	M	N.D.	N.D.	N.D.	M ⁺
71TL33	VL	VVL	VT	N.D.	L	N.D.	M	M ⁻	M ⁺
125-A	T	VL	T	VT?	L	T ⁺	M	S ⁺	M ⁺

Not detected in any samples: As, Sb, Be, Bi, B, Cd, Cs, Ge, Au, In, Ir, Mo, Os, Pd, Pt, Ag, Sn, W, Y, La, Ce, Co, Ni.

TABLE 5. QUALITATIVE ANALYSES OF MAGNETIC CONCENTRATES

Sample No.	Na	K	Mg	Ca	Sr	Ba	Al	Ti	V	Cr	Mn	Zn	Ni	Co	Sc	Ce	Nd	Er
125	N.D.	N.D.	VT	L	N.D.	S	M ⁺	S ⁺	S	T	S	VT	N.D.	N.D.	S	0	0	0
126	S	VT	S	L	N.D.	S	L	M	M	S	L ⁻	T	N.D.	N.D.	S	0	0	0
71TL33	T	T	S	L	N.D.	S ⁺	L	M	M	S	L ⁻	S	N.D.	N.D.	T	0	0	0
124TL33	N.D.	VT	T	L	S	S	L	M	M	S	VT	S	N.D.	N.D.	T	N.D.	L	0
195TL33	T	M	S	L	L	L ⁺	VL	L	L	M ⁺	M	VT	S	T	S	N.D.	VT	VT
TL-D	N.D.	T	T	L	N.D.	T	L	S	M	M ⁺	L ⁻	VT	N.D.	N.D.	S	0	0	0
7TL34	0	S	VL	VL	L	L ⁺	VL	M ⁺	L ⁻	L	L	N.D.	S	T	S	N.D.	VT	?

Not detected in any samples: Sb, As, Be, Bi, B, Cd, Cs, Ge, Au, In, Ir, Os, Pd, Pt, Sn, Y.

Detected only in 195TL33: Zr (VT), Ag (T), Pb (VT), W (VT), Mo (VT), and La (VT).

TABLE 6. QUALITATIVE ANALYSIS OF HORNBLENDE

Sample No.	Na	K	Sr	Ba	Sc	Y	La	Ce	Nd	Ti	Zr	V	Cr	Mn	Co
126	S	S	L ⁺	VL	M	N.D.	N.D.	N.D.	T	L ⁺	T	L	L ⁻	M	VT

Not detected: Sb, As, Be, Bi, Cd, Cs, Ge, Au, In, Ir, Pb, Mo, Ni, Os, Pt, Ag, Sn, W, Zn.

Differences Among Mineral Species. Na, K, Mg, Fe, Ca, Si, and Al can be considered as major elements and will not be discussed.

Sr, present in all samples, is highest in the plagioclases and groundmasses, probably because the Sr ion (valence 2; ionic radius 1.27 Å) substitutes readily for the bivalent Ca ion (ionic radius 1.06 Å) in the plagioclase crystal structure. Ba is also present in all samples, most abundantly in the biotites and groundmasses, both rather rich in potash. The bivalent Ba ion (ionic radius 1.43 Å) substitutes readily for the univalent K ion (radius 1.33 Å) where the latter is abundant. The plagioclases contain less Ba. The Sr:Ba ratios are highest for the plagioclases and groundmasses, as would be expected for high-Ca minerals. Al is an important minor constituent in the magnetic concentrates (ionic radii: trivalent Fe, 0.67 Å; trivalent Al, 0.57 Å). Sc is most abundant in the hornblende and magnetic concentrates, in both cases probably as a substitute for bivalent Mg and Fe (ionic radii: Mg, 0.78 Å; trivalent Sc, 0.83 Å; bivalent Fe, 0.83 Å).

Y and Ce occur only in the groundmasses. La shows a tendency toward a similar behavior. Yb is present in all groundmasses, but was not determined for other samples. Nd is present more or less generally. The rare earth elements are thought to substitute most readily for Ca (Tröger 1935).

Ti is highest in the hornblende, groundmasses and biotites. Zr is distributed sporadically, but where found occurs exclusively in the dark minerals, probably as a substitute for ferrous Fe (ionic radii: ferrous Fe, 0.83 Å; tetravalent Zr, 0.87 Å). V is most abundant in the hornblende, magnetic concentrates and biotites, where it probably substitutes for the ferrous or ferric ions (radii: ferrous Fe, 0.83 Å; V, 0.75 Å; ferric Fe, 0.67 Å). Cr is also highest in the hornblende, magnetic concentrates, and biotites, where it proxies for the ferric Fe ion (radii: ferric Fe, 0.67 Å; Cr, 0.65 Å). Mn is highest in the magnetic concentrates and groundmasses. A very apparent and important fact is that Ti, Zr, V, Cr, and Mn are abundant minor elements in the dark minerals. Co and Ni are rather restricted in occurrence. Zn was detected only in the magnetic concentrates, where it undoubtedly proxies for the ferrous Fe ion (ionic radii: ferrous Fe, 0.83 Å; bivalent Zn, 0.83 Å).

A startling fact is revealed when the analysis of the magnetic concentrate from the intrusion breccia (195TL33) is examined. It is the only sample that contains W, Mo, Pb and Er, and contains more Ni, Al, and Co than any other, as well as being one of two samples bearing Ag. These results show that certain minerals are characterized by certain minor elements. The minor constituents probably occur in solid solution in the crystals of the various minerals.

Differences in Content of Minor Elements in Single Minerals. Aside from the variations already noted, each single mineral species shows differences worthy of note. First, consider the plagioclases (see Table 2). The two plagioclases are characterized particularly by a special abundance of Sr and Ba. Both samples are relatively "pure," since they bear few minor constituents. Differences between the two analyses exist for Ti, Mn, Sr, and Ag. These differences are regional, since the samples came from widely separated localities.

The groundmasses as a group (see Table 3) are characterized by abundant Sr, Ba, Mg, Ti, and Mn. All are quite "impure," as they contain numerous minor elements. The presence of Ce, Nd, and Yb is notable. The elements Nd, Ce, La, Ti, Y, and Sc are more abundant in the groundmasses of biotite-rich rocks as against that of the hornblende-rich rock (71TL33). The greatest number of minor constituents is present in the groundmasses of samples 125 and 124TL33. Cr, V, and Mg are lower and Mn tends to be higher in the Chicago Creek samples (TL-B and TL-D) than in those from the districts farther north. Sc, Y, La, Ce, Nd, and Ti also tend to show some regional variation. An interesting sidelight is the difference between the two Chicago Creek samples, especially in Y, La, Ce, Nd, and Ti.

The biotites (see Table 4) are characterized by an abundance of Ba, Mn, and Ti. The Chicago Creek sample (TL-D) bears fewest minor constituents, and is thus the "purest" of the group. There are pronounced regional differences between the Chicago Creek biotite latite sample (TL-D) on the one hand and those of the Jamestown-Sugarloaf monzonite samples on the other, especially in regard to Sc, Ti, V, and Cr.

The magnetic concentrates (Table 5) bear abundant Ca, Al, Ti, V, Mn, and Cr, as well as Zn. The most notable feature of Table 5 is the pronounced difference between the intrusion breccia sample and all others. Those from the Jamestown-Sugarloaf-Gold Hill and Chicago Creek rocks are relatively "pure." As for regional variations, the intrusion breccia sample is unique. The limburgite sample also differs from most of the others. The elements Ba, Sr, Mg, K, Al, Ti, V, Cr, Mn, and Zn all show regional differences. Ti, V, Mn, and Zn are more abundant in magnetic concentrates from the Tertiary rocks than in those of the pre-Cambrian rocks in the Jamestown district (Bray, *ibid.*).

Only one hornblende was analyzed. It bears abundant Sr, Ba, Ti, V, and Cr.

As a summary of this section, the obvious conclusion is that on the basis of qualitative spectrographic analyses of individual minerals from the various rocks, a definite distinction between each rock body is possible.

This fact is important from the standpoint of correlation. Each mineral is characterized by specific minor elements.

QUANTITATIVE ANALYSES

These analyses (Tables 7, 9, 10, and 11) show the same general and relative distributions as the qualitative analyses, but give actual percentages of certain important constituents. Elements not included in the tables are not necessarily absent.

TABLE 7. QUANTITATIVE ANALYSES OF PLAGIOCLASE

Sample No.	Δ Log. <i>E</i> Mg	% SrO	% BaO	% TiO ₂	% V ₂ O ₅	% Cr ₂ O ₃	% MnO	Δ Log. <i>E</i> Fe	SrO:BaO Ratio	V ₂ O ₅ :Cr ₂ O ₃ Ratio
125	0.51	0.185	0.0305	0.0124	0.0012	N.D.	0.019	0.61	6.1	I
126	0.39	0.230	0.0370	0.0150	0.0031	0.0003	0.0105	0.44	6.2	10
71TL33	0.52	0.300	0.0630	0.0690	0.0035	N.D.	0.0285	0.57	4.8	I
124TL33	0.83	0.360	0.0690	0.0500	0.0038	N.D.	0.0360	1.01	5.2	I

I—Infinite.

The Plagioclases. Table 7 gives quantitative analyses of 4 plagioclases. Table 8 gives their compositions as determined from refractive indices. The most abundant constituent is SrO, a fact to be expected from what has already been said. BaO is next to SrO in the list of abundances. The

TABLE 8. COMPOSITIONS OF THE PLAGIOCLASE FELDSPARS

Sample No.	Rock	Composition
125	Biotite monzonite (Jamestown)	Ab ₅₈ An ₄₂
126	Hornblende monzonite (Jamestown)	Ab ₅₈ An ₄₂
71TL33	Hornblende monzonite (Sugarloaf Mt.)	Ab ₆₂ An ₃₈
124TL33	Biotite latite (Logan Mine, Gold Hill)	Ab ₆₂ An ₃₈
T1-B	Biotite latite (Chicago Creeks)	Ab ₅₈ An ₄₂
T1-D	Biotite latite (Chicago Creeks)	Ab ₅₈ An ₄₂

plagioclase from the Gold Hill biotite latite (124TL33) is definitely the most "impure" of the group. The Jamestown biotite monzonite sample (125) is definitely the "purest." The universal presence of V₂O₅ is noteworthy, as is the fact that this constituent is always much more abundant than Cr₂O₃, as the V₂O₅:Cr₂O₃ ratios reveal. The SrO:BaO ratios gen-

TABLE 9. QUANTITATIVE ANALYSES OF GROUNDMASS SAMPLES

Sample No.	Δ Log. E Mg	% SrO	% BaO	% Sc ₂ O ₃	% TiO ₂	% V ₂ O ₅	% Cr ₂ O ₃	% MnO	Δ Log. E Fe	SrO:BaO Ratio	V ₂ O ₅ :Cr ₂ O ₃ Ratio
125	0.86	0.083	0.093	0.0049	0.33	0.0064	0.0001	0.075	1.70	0.9	64
126	0.50	0.124	0.054	0.0020	0.18	0.0080	0.0002	0.028	1.15	2.3	40
71TL33	0.63	0.185	0.046	N.D.	0.10	0.0061	0.0002	0.040	1.05	4.0	30
124TL33	0.63	0.076	0.044	0.0025	0.20	0.0084	0.0007	0.052	1.30	1.7	12
TL-D	0.49	0.150	0.060	0.0022	0.105	0.0023	0.00014	0.045	0.70	2.5	20

TABLE 10. QUANTITATIVE ANALYSES OF BIOTITE

Sample No.	% SrO	% BaO	% Sc ₂ O ₃	Δ Log. E La	% TiO ₂	% V ₂ O ₅	% Cr ₂ O ₃	Δ Log. E Mn	Δ Log. E Co	% NiO	% ZnO	SrO:BaO Ratio	V ₂ O ₅ :Cr ₂ O ₃ Ratio
125	0.037	>0.1	0.0022	-1.17	5.6*	0.12	0.046	-0.46	-0.74	0.0064	0.092	<0.3	2.5
124TL33	0.054	>0.1	0.0028	-0.90	10.0*	0.14	0.0108	-0.60	-0.78	0.0073	0.140	<0.5	10.0
TL-D	0.016	>0.1	0.0045	N.D.	3.7*	0.03	0.0054	-0.66	-1.19	N.D.	0.140	<0.2	6.0

* Really means greater than 1.3%

TABLE 11. QUANTITATIVE ANALYSIS OF HORNBLLENDE

Sample No.	% SrO	% BaO	% Sc ₂ O ₃	Δ Log. E La	% TiO ₂	% V ₂ O ₅	% Cr ₂ O ₃	Δ Log. E Mn	Δ Log. E Co	SrO:BaO Ratio	V ₂ O ₅ :Cr ₂ O ₃ Ratio
71TL33	0.083	0.012	0.015	-1.06	2.3*	0.06	0.035	-0.68	-1.04	6.9	1.6

* Really means greater than 1.3%

erally exceed a magnitude of 5, far greater than the same ratios for potash feldspars (Bray, *ibid.*). This is because Sr has a special tendency to substitute for Ca, and Ba for K.

Notable in Table 7 is the fact that the Jamestown plagioclases (125 and 126) are quite similar in their analyses, as is the case for the Gold Hill Sugarloaf samples (71TL33 and 124TL33). These two major groups differ from each other for practically every minor constituent. The Jamestown SrO:BaO ratios are in the neighborhood of 6, whereas those for the other group are about 5. The plagioclase from these Tertiary dike rocks contains more SrO, BaO, TiO₂, V₂O₅, FeO and MnO than any other plagioclases (some from pre-Cambrian rocks and some from Tertiary stocks) analyzed by the author. To make desired comparisons see the paper by Bray (*ibid.*).

The Groundmasses. Quantitative analyses of groundmasses are listed in Table 9. Obvious facts are as follows: TiO₂ is the most abundant minor constituent given in per cent. SrO is next. The Jamestown biotite monzonite sample (125) is "purest," and the Chicago Creek sample the most "impure." Cr₂O₃ and V₂O₅ are universal, the latter in all cases more abundant than the former (see ratios), as was the case for plagioclase. The SrO:BaO ratios are generally less than 2.5, much smaller than those for the plagioclases. As far as regional differences are concerned, the Chicago Creek sample (TL-D) differs materially from all the others. The Jamestown and Gold Hill-Sugarloaf groups are not as well defined as was the case for the plagioclases.

The Biotites. Quantitative analyses of the biotites appear in Table 10. TiO₂, BaO, and ZnO are the most abundant minor constituents. (Zn was detected in the quantitative and not in the qualitative analyses because of differences in method.) Sc₂O₃, V₂O₅, Cr₂O₃, Co and NiO are also characteristic. The SrO:BaO ratios are all less than 0.5, indicating that BaO is more abundant than SrO in all cases, a condition greatly different from that pertaining to the plagioclases and groundmasses. The V₂O₅:Cr₂O₃ ratios are rather large.

As for regional differences, the T1-D sample differs distinctly from the others. Recognizable regional variations exist for SrO, La, TiO₂, and Cr₂O₃. These Tertiary biotites bear more BaO than those from the pre-Cambrian and Tertiary stocks of the Jamestown district. Their SrO:BaO ratios are less than those for the biotites of the other rocks mentioned. Sc₂O₃, La, and Mn are present in smaller quantities in the Tertiary than in the Jamestown pre-Cambrian biotites (Bray, *ibid.*).

Hornblende. Only one hornblende was analyzed. It is rich in TiO₂, SrO,

and V_2O_5 , and has the highest $SrO:BaO$ and $V_2O_5:Cr_2O_3$ ratios of any of the minerals analyzed.

SUMMARY AND CONCLUSIONS

Special "geochemical affinities" are noticeable in the analyses. That is, certain minor elements are most abundant in those minerals rich in particular major (or "essential") elements. Typical examples of this condition are the tendencies of Ba to substitute for K, Sr for Ca, V and Cr for Fe, Zn for ferrous Fe, and Sc for ferrous Fe and Mg. These "geochemical affinities" depend upon the ionic properties of the various elements concerned. "Geochemical pairs," or pairs of minor elements distributed in an exactly similar manner, are also notable. Examples are V and Cr, Ni and Co.

Ratios between similar minor constituents, such as $SrO:BaO$ and $V_2O_5:Cr_2O_3$, are useful for indexing the relative abundance of these constituents. The ratios mentioned showed systematic differences from mineral to mineral, and from district to district.

Analyses of minerals from Tertiary dikes showed distinct differences from those of the same minerals in Tertiary and pre-Cambrian stocks. The rock analyses show similar behavior.

Important "index elements," or those that appear in different rocks and minerals in systematically different quantities, are as follows: Pb, Ni, Co, Sc, Cr, V, La, Y, Ce, Nd, Ti, and Mn. Use of these elements permits a grouping or correlation of the various rock types as well as a rough regional classification. Both qualitative and quantitative analyses, especially those of minerals, are useful in this respect. Each mineral species is characterized by particular minor constituents.

The data here presented seem to indicate that the spectrograph is destined to become an important geological tool, not only for purely petrological investigations, but for practical commercial purposes as well.

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THE MINERALOGY AND PARAGENESIS OF THE VARISCITE NODULES FROM NEAR FAIRFIELD, UTAH. PART 3.

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(Continued from p. 372)

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ORIGIN OF THE VARISCITE AND LATER PHOSPHATES

CHARACTER OF THE DEPOSITING SOLUTIONS

A question of prime importance in the origin of the nodules is whether they were formed from ascending hydrothermal solutions or from ground waters. It is believed that both the variscite and the later phosphates were deposited from ground waters. Pertinent evidence of their origin comes (1) from the minerals found in the nodules and in the surrounding country rock; (2) from the structure of the deposit; (3) from a comparison of the Fairfield deposit with the mineralogy and structure of other variscite deposits; and (4) from a consideration of the origin of similar phosphates in other types of deposits.

A mineral assemblage similar to that found at Fairfield is confined almost wholly to similar variscite deposits. Quartz and calcite, variscite, wardite, pseudowavellite, and members of the apatite group are the only minerals found in other deposits of known hydrothermal origin. Quartz and calcite have no significance because of their ubiquitous distribution. Pseudowavellite occurs in hydrothermal iron deposits in Germany (Laubmann, 1922), but in association with wavellite and limonite, and of supergene origin. Variscite has been found in the Marion mine of the Mercur district, five miles north of the Fairfield deposit, but its mode of occurrence is not known; supergene activity has been indicated in this area, and kaolin coats the variscite. Wardite (soumansite) is described by Lacroix (1910) as occurring in the Montebas tin pegmatites; the crystals are planted on the walls of solution cavities in amblygonite, and apparently followed the alteration of a previously formed hydrous sodium aluminum phosphate (morinite); it is not necessarily genetically

related to the amblygonite. Members of the apatite group are commonly of hydrothermal origin, but in general these are fluor-apatites or chlor-apatites; hydroxyl and carbonate members are abundant in phosphorite deposits.

Some of the wardite at Fairfield is divided optically into four biaxial segments; this may be due to inversion from a higher temperature form. It does not revert to this form when heated to near 100° C., but the inversion may be sluggish. It may be a characteristic twinning and not due to inversion. Some of the apatite members show a similar optical segmentation; but apatite members occurring with coal and sedimentary iron ores (Deans, 1938), and in cavities in sedimentary phosphorite nodules show this same optical effect. It is probably a twin-growth phenomenon and not due to an inversion. Both gordonite and variscite permanently lose considerable H₂O at 110° C.; they could not have existed in dry rocks without dehydration at temperatures as high as this. These facts suggest little concerning the temperature of formation, but they do not require that the temperature be high.

The wall rock material gives only negative hydrothermal evidence. The chert, comprising the bulk of the material in the deposit, may be of hydrothermal origin. Gilluly (1932) describes large tabular masses of chert (jasper) in the Great Blue limestone, some directly associated with metallization and much not visibly so, and attributes them all to a hydrothermal origin; the chert containing the variscite may be related to these bodies. However, they formed at some time previous to the formation of the variscite, as shown by its faulting and brecciation preceding the deposition of variscite. The alunite may be either of hydrothermal or ground-water origin, probably the latter; it likewise must have formed earlier than the variscite, since it was brecciated by the early faulting. The limonite is of doubtless supergene origin, but it formed after the phosphates.

There is a notable absence of any typically hydrothermal minerals. Sulfides are lacking; common hydrothermal gangue materials are found only in traces, and most of this not related to the phosphates. Only phosphates were deposited throughout the whole mineralization history of the nodules, with the exception of minor quartz veinlets following the fracturing of the variscite. This mineralization would require a most unusual and unlikely hydrothermal solution, but not an unusual ground-water.

The highly shattered nature of the wall-rock and the very open, blocky character of the faulting indicate deformation at very shallow depth, and thus within reach of moving ground-waters.

A comparison of the Fairfield deposit with other variscite deposits in

Utah and Nevada serves to emphasize some of the features considered above. Little is known in these other occurrences about the phosphate minerals associated with the variscite; pseudowavellite and wardite appear in general to be the principal alteration minerals. Other phosphates may be present but have not been identified.

Zalinski (1909) and Sterrett (1909) have described a variscite deposit (Amatrice Hill) located about 25 miles northwest of the Fairfield deposit and nine miles west of Stockton. The variscite occurs as nodules along strong fissures in a crushed and shattered zone which parallels the bedding of upper Carboniferous limestone. The limestone grades upward into a quartzite which is barren of variscite. Variscite, wardite and probably other similar phosphates comprise the nodules, together with a great abundance of chalcedony; much of the variscite is impregnated with chalcedony. Limonite and crushed chert fragments are abundant. Fresh pyrite is found enclosed in variscite. It is believed there have been successive periods of crushing and fracturing with subsequent deposition of various minerals in cracks and seams. The variscite continued to only twelve feet below the surface, and is thus believed to be of local origin. In most features as described by Zalinski and Sterrett this would seem to be identical with the Fairfield deposit.

The deposit north of Lucin, Utah, has been described briefly by Pepperberg (1911) and Sterrett (1911). The country rock is a moderately dipping Pennsylvanian (?) quartzite, locally calcareous, with intercalated limestone beds. Tertiary intrusives are nearby. The variscite and associated minerals occur in strongly brecciated quartzite (or more probably a silicified limestone, according to Sterrett), and the mineralization follows the strike intermittently for 600 feet. The angular openings between quartzite breccia fragments have been filled with the phosphates, but they have not replaced the siliceous material. Much of the variscite is in nodules and balls; a small amount forms discontinuous veins. This deposit has yielded crystals of variscite and metavariscite occurring in cavities of the massive variscite (Schaller, 1912).

A number of deposits occur in Esmeralda County, Nevada; these have been described by Sterrett (1910, 1911). They occur in a variety of rocks, principally altered rhyolites, but also in altered trachytes, cherty limestone, jasperoid and sandy shale. Where the variscite occurs the rocks are faulted and brecciated, and considerably altered.

The variscite occurs as a filling in fissures and joints, replacing other minerals, and as irregular and nodular segregations. The variscite not only fills many seams and joints in the rocks, but the crevices between shattered and brecciated fragments of rocks along the fissures. . . . Some of the larger veinlets can be traced for many feet; the smaller ones are less persistent and vary in direction. The individual seams of variscite vary from paper thickness to 2 or 3 inches in width. Locally they may bulge out into nodular masses several

inches across. . . . The different deposits in the same region have no connection with one another, but appear to be of local origin. (Sterrett, 1911, p. 889).

Some of the variscite is coated with yellow and black phosphates; the yellow material may be pseudowavellite. In several of these deposits "turquoise has been found within a few yards of variscite in similar forms of occurrence" (Sterrett, 1911, p. 889).

Pepperberg (1911) sums up the striking similarities between all of these deposits as follows:

The conditions surrounding the variscite deposits of Utah are similar in every case so far reported; that is, the mineral is deposited as a cementing material in brecciated limestone, quartzites or igneous rocks. It is usually associated with chalcedony (and chert) and is much younger geologically than the rocks in which it is found. Several of the deposits are found in rocks of the same geological age, but they seem to be strictly local deposits, and, from the evidence at hand, there is no apparent connection between them. Whether there is any relation between the variscite and the rock-phosphate deposits of Idaho, Utah, and Wyoming is not known . . . (p. 233).

His remarks apply as well to the Nevada as to the Utah deposits. In none of the deposits is there a suggestion of hydrothermal origin; but there is overwhelming evidence for a purely local origin, a deposition from local solutions, of necessity ground-waters.

An innumerable variety of phosphates of calcium and (or) aluminum, generally with water, have been described from deposits of known supergene origin. With the exception of apatite, minerals with compositions similar to these are not derived from solutions of igneous origin.

To conclude, there is no doubt that the Fairfield and other similar variscite deposits have been derived from ground waters, because:

1. None of the normal hydrothermal minerals are associated with the deposit.
2. The minerals present are hydrates undoubtedly formed at near surface temperatures.
3. Phosphatic ground waters are common in nature.
4. Ground waters commonly form similar phosphate minerals.
5. Phosphatic material is available in the surrounding rocks.
6. The deposit is in a brecciated zone easily accessible to ground waters.

SOURCE OF THE PHOSPHATE MATERIAL

The Permian strata (Phosphoria) of Utah and Idaho contain commercial deposits of phosphorite, stratigraphically above the Fairfield ("Great Blue") and Amatrice Hill and Lucin (Weber) rocks. In the region of Fairfield, rock phosphate likewise underlies at some depth the "Great Blue." Non-economic concentrations of phosphate very likely occur locally in intermediate stratigraphic positions. Such evident availability of material for the variscite deposits points to it as the most reasonable source. Pepperberg (1911) has suggested this source.

In the Nevada deposits, largely associated with volcanic rocks, the phosphate may be derived from disseminated apatite in the host rocks. A conversion of apatite into phosphates analogous to these is exemplified by pseudomorphs of turquoise after apatite (Dana, 1892, p. 845). The phosphate to form the turquoise of Los Cerillos, New Mexico, is considered by Silliman (in Clarke and Diller, 1886) to be derived possibly from apatite in the enclosing "fine-grained feldspathic rock."

GEOCHEMISTRY OF PHOSPHATES

Clarke (1920, pp. 515-526; 1924) has collected and summarized the experimental and geological data concerning the geochemistry of phosphates; his publications mainly have been drawn on for the discussion of this section. His references will not be repeated here.

Calcium phosphate is freely soluble in carbonated waters, but is precipitated in the presence of excess CaCO_3 . Thus, phosphorites in limestone exposed to surface waters are concentrated further by selective removal of the calcite forming the limestone. Eventually the phosphorite will itself dissolve in surface waters and migrate downward, probably to be precipitated in underlying limestone as nodular and other forms of phosphorite.

When iron or aluminum hydroxides are added to a carbonated water solution of calcium phosphate, the phosphate is precipitated with the iron or aluminum, probably as a basic hydrate. Clarke (1920, p. 516) says: "By reactions of this kind, probably, many well-known minerals have been produced." He includes among minerals probably formed in this way variscite, wavellite, turquoise, and wardite, among the phosphates, and the isodimorphous equivalents of variscite, strengite and phosphosiderite.

Guano deposits, which contain much phosphate, have afforded good examples of the effect of phosphate solutions on various kinds of rocks. Where the rock underlying guano is limestone, percolating waters have reacted to form principally hydrous calcium phosphates, which may be acid. Where the underlying rock is igneous or contains clay, the reaction normally has developed phosphates of aluminum, with some iron. Analyses of material developed in igneous rocks underlying guano, in several cases approach the composition of variscite. More complex compositions are common, including phosphates with alkalies, magnesia, or ammonia.

The common occurrence of turquoise in altered volcanic rocks is suggestive of a similar mechanism, the deposition of phosphate by aluminum in the rock. Clarke and Diller (1886) have noted this. The presence of turquoise accompanying variscite in some of the Nevada deposits noted by Sterrett (1911, p. 889) suggests that the presence of some copper in the

rock may cause the deposition of turquoise instead of variscite, other conditions being much the same.

APPLICATION OF THE GEOCHEMISTRY TO THE FAIRFIELD DEPOSIT

The precipitation of aluminum phosphates by the reaction of phosphatic waters on aluminous rocks seems readily to explain the variscite deposits in altered volcanic rocks; some complications seem to arise in applying these ideas to variscite deposits in limestones, as are most of the Utah occurrences. At Fairfield, Kunz (1894) has described the Fairfield variscite as occurring in and below a ferruginous slate; Montgomery (personal communication) questions the existence there of any slate or shale. If such material were there, aluminum would be readily available; however most limestones contain some clay material as impurity in widely varying amounts.

The frequent occurrence of variscite along the major fractures in brecciated limestones may have an important bearing on its origin. As noted above, calcium phosphate is readily soluble in carbonated solutions, but is precipitated if the solution stands over solid CaCO_3 . Normal surface waters would dissolve calcium phosphate from surface phosphorites, and after percolating slowly down into immediately underlying limestone, would reprecipitate the material as calcium phosphate by replacing the calcium carbonate.

However, these surface waters containing dissolved calcium phosphate may travel downward rapidly along permeable or even open fracture zones; since the precipitating effect of CaCO_3 is slow, steadily moving solutions may lose only a very little of their phosphate when they reach a moderate depth. Thus, at some depth these solutions could meet aluminous material (shales, clay) which would act as a strong precipitant on the dissolved phosphate. It is possible that the alunite present in the Fairfield deposit contributed alumina to precipitate the phosphate; the variscite certainly replaced alunite in small amounts, but alunite is not normally the host of the variscite. It is possible, too, that alunite contributed SO_4 to the solutions; this may have some precipitating effect on phosphatic waters. In this way variscite could deposit at depth in a limestone terrain from surface waters.

The alteration minerals of the variscite at Fairfield have probably not formed as a result of further introduction of phosphate, but by a later reworking of the phosphate in the variscite. This suggests that the phosphate was introduced throughout some period which ended completely, and perhaps abruptly, with the cessation of phosphatic solutions. Such a limited period of introduction would be expected if a phosphorite bed at the surface contributed the phosphate material; when surface weathering

and erosion had removed the phosphorite bed, the source of material would be gone and downward moving solutions would no longer be phosphate-bearing.

What the changes in environment were which brought about the alteration of the variscite are not known. Both the variscite and its later alterations probably formed below the water table, since strongly oxidizing conditions appear to have followed all of the phosphate mineralization, as shown by the definitely later introduction of limonite and clay material. Cameron and Hurst (1905, cited by Clarke, 1920) have shown that the reaction in solution between calcium phosphate and aluminum develops an acid medium with the precipitation of a basic phosphate. Since ground waters in a limestone area are alkaline, this reaction in nature may develop either slightly acid solutions or solutions less alkaline than usual. Thus the variscite may have been developed in a nearly neutral environment. With the cessation of introduction of phosphate, the solutions probably became more alkaline; it is under these conditions, perhaps, that the variscite was reacted upon to form the later phosphate minerals.

Some evidence for this is shown by the fact that variscite is insoluble in strong acids, but is readily soluble in strong alkalis. There is considerable evidence in the Fairfield nodules that variscite at one time or another was removed by solution as well as by replacement; this suggests alkaline solutions as the dissolving agency.

A few brief experiments, conducted by Dr. Clifford Frondel, assisted by the writer, were made to determine the effect of various alkaline solutions on variscite. Five water solutions were prepared in open beakers as follows:

1. 2 g. Ca(OH)_2 + 350 cc. H_2O
2. 2 g. Ca(OH)_2 + 0.175 g. NaOH + 350 cc. H_2O
3. 2 g. Ca(OH)_2 + 3.5 g. NaOH + 350 cc. H_2O
4. 1 g. Ca(OH)_2 + 1.7 g. NaOH + 350 cc. H_2O
5. 2 g. Ca(OH)_2 + 20 g. NaCl + 350 cc. H_2O

To each of these solutions was added a small amount of powdered variscite and a few small fragments of variscite. All were maintained at, or near, their boiling point for a maximum time of two weeks. Additional water was added at intervals to maintain the original volume.

Of the five used, only solutions 3 and 4 (the two stronger NaOH + Ca(OH)_2 solutions) showed any effect in two weeks. The NaOH + Ca(OH)_2 solutions caused marked effects in less than 48 hours; coarse fragments of variscite were noticeably rounded, and on them was developed a dark gelatinous coating about one-half millimeter in thickness. When dried in the air, the dark shell separated from the variscite and

fell into fragments; the remaining variscite core, when broken, showed a thin, hard, white layer completely surrounding it. Under the microscope the dark loose shell was isotropic and nearly opaque, and had an index of refraction around 1.51; the white layer was likewise isotropic and very clouded, and had an index of refraction a little below 1.620. X-ray powder photographs of these two products show only a few faint lines, even after long exposure. Photographs of the two products are identical and their lines match the strong lines of pseudowavellite and deltaite photographs. Thus there is developed an incipient crystallization of a substance related structurally and chemically to the principal alteration mineral in the nodules.

This experimental evidence increases the probability that the alterations of variscite were developed from alkaline solutions; but the natural waters were undoubtedly much more dilute and cooler than those used in these experiments. However, given ample time, the same results would be expected from dilute, cool solutions of this same general type.

The compositional variations in the solutions which deposited the secondary phosphates are not known. The first period of alteration, producing principally the banded shells, veinlets and spherules of pseudowavellite, wardite and millisite must have seen an increase with time in the quantity of alkalis, especially soda, in the ground waters. Beginning late in the wardite period, solution of the variscite exceeded deposition by replacement to form solution openings, and this dissolution of variscite probably continued after the wardite ceased forming. This suggests that the increased content of alkalis raised the alkalinity of the solutions to a point where their only reaction was to dissolve variscite. The alkalinity apparently decreased to nearly its original state, and the replacement to form the inner bands of pseudowavellite took place. This ended the quantitatively important alteration. The temporary introduction of alkalis into the ground waters may correspond with the surface weathering of a layer of shaly material interbedded with the limestones; in such weathering the soda would be largely freed to the solutions, while most of the potash would be retained in the soil by adsorption (Clarke, 1920, p. 206).

The second alteration stage started, apparently, with an excess of magnesia over lime or alkalis, and gordonite was deposited, by replacement of variscite and precipitation as crystals in cavities near variscite. The rest of the stage is largely the formation of minor quantities of calcium aluminum phosphates, the equilibrium conditions of which are not known. The conditions of formation of sterrettite are not known, nor is its sequence closely established.

The third stage of alteration represents perhaps a reversion to condi-

tions similar to, but much milder than, the original stage of the alterations, and is represented by the precipitation in cavities of minor amounts of pseudowavellite, and is in only a vague way a reaction of the solutions with the variscite.

The final stage of phosphate deposition was characterized by a lack of aluminum and the renewed presence of alkalies, to form apatite members, similar to those found in phosphorites near the surface.

Indefinitely later the ground-water level sank below the level of the variscite; limonite and other earthy material came in to surround the nodules and replace the residual limestone.

SUMMARY OF ORIGIN

Phosphorite beds at the surface were attacked by carbonated surface waters, and the resultant solutions of calcium phosphate moved downward along throughgoing channels into the zone below the water table. Here the solutions traversed aluminous material, perhaps shales, and deposited the phosphate as the aluminum salt, variscite. This reaction perhaps caused a decrease in the alkalinity of the solutions. When the phosphorite was completely removed at the surface, the downward-moving ground waters became free of phosphate material, and returned to their usual alkaline state. This return to stronger alkalinity caused a reaction with the variscite to replace it with calcium aluminum phosphate (pseudowavellite), an introduction of only calcium. Soda then became an important constituent of the solutions, perhaps derived from the weathering of shales or shaly limestones exposed at the surface; this resulted in the deposition of millisite and wardite. The soda increased the alkalinity of the solutions, eventually to the point where the deposition of wardite did not keep pace with the removal of variscite by solution. The solutions then returned to their normal alkalinity, probably with the removal of the shale and the exposure again of limestones, and again deposited pseudowavellite in place of the variscite. This ended the bulk of the mineralization. The stages following this are represented in the nodules primarily by rare crystals in the solution cavities, at first aluminum phosphates of magnesium (gordonite), followed by calcium. In the final stage aluminum is absent, and alkalies reappear. The equilibrium conditions controlling the deposition of these is not known, so that the state of the solutions forming them cannot be surmised. With the lowering of the water table below the variscite, oxidizing conditions ensued, with the deposition of abundant limonite.

It is believed that one of the major factors permitting the deposition of variscite at Fairfield, and probably some other deposits, was the existence of open fissures which permitted the surface solutions containing dis-

solved calcium phosphate to move rapidly downward through underlying limestone into rocks containing aluminum. In the normal course, ground waters with dissolved calcium phosphate seep down into underlying limestones, where the phosphate is leisurely precipitated by the excess of calcium carbonate. Where open channels allow more rapid descent of the solutions, the precipitating effect of the limestone is not so effective, and phosphate-bearing solutions can thus reach aluminous rocks, and the aluminum will act as the precipitant. The equilibrium conditions which determined the deposition of variscite rather than some other aluminum phosphate (such as wavellite) are not known.

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GRIPHITE, A HYDROPHOSPHATE GARNETOID

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ABSTRACT

Griphite is cubic and its structure is similar to that of garnets. The unit cell contains $8[(\text{Na}, \text{Al}, \text{Ca}, \text{Fe})_3\text{Mn}_2(\text{PO}_4)_{2.5}(\text{OH})_2]$ and this formula represents a complex example of $\text{X}_3\text{Y}_2(\text{ZO}_4)_{3-m}(\text{OH})_{4m}$. The latter is a variation of $\text{X}_3\text{Y}_2(\text{ZO}_4)_3$ which is necessary to accommodate the hydrogarnets and plazolite. An alternate formula is suggested and cannot be eliminated as a possibility, namely, $8[(\text{Na}, \text{Ca}, \text{Fe}, \text{Mn})_3(\text{Al}, \text{Mn})_2(\text{PO}_4)_{2.5}(\text{OH})_2]$. The space group could not be determined but appears to have lower symmetry than that of garnet ($O_h^{10} = Ia\bar{3}d$). Griphite and other substances with structures similar to garnet are classified as garnetoids.

INTRODUCTION

The name griphite was proposed in 1891 by W. P. Headden (1) for a hydrated phosphate of manganese, aluminum, sodium, calcium, and iron. Griphite ($\gamma\rho\iota\phi\omicron\varsigma$ = an enigma) seemed an appropriate name because of the chemical complexity of this mineral and the apparent absence of a simple relation to any other known mineral.

The present investigation will demonstrate that the chemical composition, physical properties and x-ray diffraction data for griphite permit its classification as a garnetoid.¹ Several interesting implications are to be attached to the fact that a sodium-calcium-manganese-aluminum hydrophosphate with garnet-like structure exists. Its existence suggests the possible replacement of calcium and silicon by sodium and phosphorus in garnets and garnetoids. Of particular interest is the possible entry of these constituents into the lattice of cubic tricalcium aluminate hexahydrate, one of the well established hydration products of portland cement, because both sodium and phosphorus are considered objectionable constituents in cement clinker, if they exceed certain limits.

Ionic substitutions involving sodium and phosphorus are relatively uncommon among garnets, or their occurrence has been overlooked as only a few analyses report Na_2O (about 2 per cent being the maximum amount), and the analyses that indicate P_2O_5 are extremely rare (the amount of P_2O_5 being less than 1 per cent). Although the writer (2) has demonstrated in ellestadite almost complete replacement of PO_4 -groups by SO_4 - and SiO_4 -groups in the structure of apatite, nothing conversely similar has been previously shown among the garnets. Thus the rather

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¹ The term "garnetoid" is introduced to designate those substances which are not primarily silicates but have structures similar to that of true garnets. Examples are the various hydrogarnets, berzeliite, plazolite, and griphite.

complete substitution of PO_4 -groups for SiO_4 -groups encountered in griphite is noteworthy.

Cubic tricalcium aluminate hexahydrate has recently been investigated thoroughly by E. P. Flint, H. F. McMurdie, and L. S. Wells (3). These investigators likewise demonstrated the existence of a hydrogarnet corresponding to andradite and having the composition $3\text{CaO} \cdot \text{Fe}_2\text{O}_3 \cdot 6\text{H}_2\text{O}$. The structural data presented by these authors, the data obtained for berzeliite by W. Bubeck and F. Machatschki (4), and the complete structural investigation of plazolite presented by A. Pabst (5), are invaluable in the establishment of the relationship of griphite to other garnetoids.

PHYSICAL PROPERTIES OF GRIPHITE

Headden (1) described griphite as "amorphous" because it is isotropic on microscopic examination and no crystal forms were observed. However, the relationships among the properties of griphite, plazolite,² and grossularite are quite apparent when tabulated.

	<i>Griphite</i>	<i>Plazolite</i>	<i>Grossularite</i>
Hardness	$5\frac{1}{2}$	$6\frac{1}{2}$ (?)	6
Specific gravity	3.40	3.13	3.58 ca.
Refractive index	1.64-1.66	1.675	1.735
Fusibility	Easily fused	Fusible	3

Griphite apparently lacks the ability to form euhedral crystals, differing from garnets in this respect. However, it is not amorphous but exhibits discontinuous vectorial properties, as is demonstrated by the x-ray diffraction pattern which it produces. Both griphite and plazolite are soluble in HCl, whereas true garnets (except schorlomite) are difficultly soluble or insoluble in ordinary acids. Absence of cleavage is characteristic of the garnetoids as well as the garnets.

X-RAY DIFFRACTION DATA

Powder diffraction patterns were obtained for griphite (near Harney City, Pennington County, South Dakota; U.S.N.M. No. R-5315, obtained from Headden), grossularite (6), schorlomite (Magnet Cove, Arkansas), uvarovite (Washington, Nevada County, California) and andradite (near Randsburg, California) through the use of unfiltered iron radiation and precision cameras (M. J. Buerger's model) with $r=57.3$ mm. The cell dimensions of these are as follows, omitting andradite:

	<i>Griphite</i>	<i>Schorlomite</i>	<i>Uvarovite</i>	<i>Grossularite</i>
a_0	12.26	12.09	11.97	11.87
		(all ± 0.01 Å)		

² D. S. Belyankin and V. P. Petrov (*Am. Mineral.*, **26**, 450-453, 1941) have recently shown through reexamination of hibsichte that this substance is similar to plazolite.

TABLE 1. COMPARISON OF POWDER DIFFRACTION DIAGRAMS
(Unfiltered Fe Radiation— $r=57.3$ mm.)

No.	Indices*	Schorlomite**		Griphite			Hausmannite†		Mn-berzeliiite‡	
		$d_{\text{expt.}}$	I	$d_{\text{calc.}}$	$d_{\text{expt.}}$	I	d	I	$I_{\text{calc.}}$	$I_{\text{expt.}}$
1	220	4.31	<1		—				≈ 0	—
2	320	—		3.401	3.39	1	3.08	m	—	
3	β 400	3.34	<1	(3.37)						
4	321	—		3.277	3.264	$\frac{1}{2}$			5.1	3
5	400	3.026	5	3.066	3.066	4			13	10
6	β 420	2.975	2	(3.01)	2.97	4			—	
7	410, 322	—		2.974						
8	411, 330	—		2.890	2.884	1	—			
9	420	2.702	8	2.742	2.743	10	2.755	s	42	>20
10	332	2.584	<1		—				8.3	7
11	422	2.468	6	2.503	2.498	4	2.478	s	21.2	12
12	431	2.366	1	2.404	2.408	1			3.2	3
13	—	—		—	2.362	1	2.345	m		
14	520, 432	—		2.279	2.281	3			—	
15	521	2.205	1		—				≈ 0	—
16	610	—		2.015	2.018	3	2.032	m	—	
17	611, 532	1.964	2		—				0.4	—
18	620	1.909	<1		—				0.4	—
19	541, β 640	1.845	<1		—				0.1	—
20	630, 542	—		1.828	1.832	2			—	
21	631	1.781	2		—		1.789	m	2.3	3
22	444	1.743	1	1.770	1.770	2			8	8
23	640	1.679	7	1.700	1.700	3			20.3	20
24	642	1.614	>10	1.638	1.637	6			34.3	>20
25	730	—		1.610	1.604	1			—	
26	732, 651	—		1.557	1.563	1	1.574	m	2.2	1-2
27	800	1.512	3	1.533	1.536	1	1.538	s	8.5	8
28	820, 644	—		1.487	1.478	2			0.05	—
29	822, 660	1.424	<1		—		1.437	m	0.2	—
30	840	1.351	5		—				9.7	10
31	842	1.319	5	1.338	1.344	1			17.2	15
32	921, 761, 655	—		1.322	1.325	1			3.1	2
33	664	1.290	4	1.307	1.303	1			7.2	8

* The indices do not pertain to hausmannite.

** Several of the weaker β -lines are omitted.† Only the more intense lines are listed. Data from G. Aminoff: *Zeits. Krist.*, **64**, 475 (1926).‡ Data from W. Bubeck and F. Machatschki: *op. cit.* Reflection from 211 was not observed by these authors although the calculated intensity is 6. Planes 653 and 752 gave observed intensities 2 and 1, respectively.

The cell edges of schorlomite and uvarovite are given, although analyses of these specimens are not available, because published measurements for these garnets are very rare in the literature. In addition it was observed that the diffraction pattern of schorlomite is not significantly different from those of other garnets. Therefore schorlomite is more closely related to the garnets than the garnetoids.

The similarities of the powder diffraction patterns of schorlomite and griphite are shown in Fig. 1 and the measurements obtained from these are given in Table 1. With one exception (line No. 13, Table 1) all of the lines obtained from the sample of griphite yield cubic indices. This line, presumably extraneous, may have been contributed by hausmannite. It was not feasible to completely eliminate one of the contaminating substances, a mineral which appears deep red-brown to opaque in thin section and resembles hausmannite in other respects.

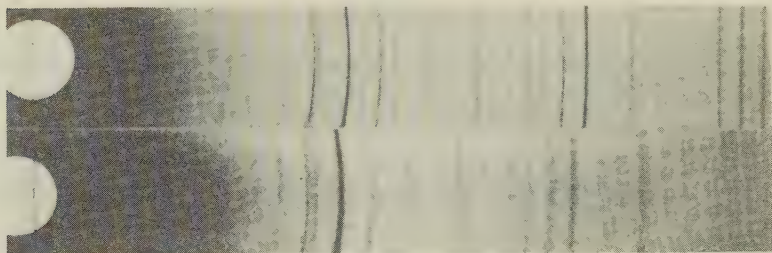


FIG. 1. Powder diffraction patterns of schorlomite (above) and griphite.
Unfiltered Fe radiation.

If hausmannite is to be assumed as a contaminating substance, the diffraction pattern must be interpreted through consideration of all of the intense lines of this mineral, and these are shown in Table 1 for comparison. However, this assumption does not explain the occurrence of reflections from 320, 411, 730, 630 or 542, and 520 or 432, although the first two of these are similar in spacing to β -lines. Of significance are the similarities in intensities between the corresponding lines of griphite and Mn-berzeliite. The experimental and calculated intensities for Mn-berzeliite obtained by Bubeck and Machatschki (4) are given for comparison (Table 1).

Notwithstanding the similarities, there are certain differences among the patterns of schorlomite, griphite, and Mn-berzeliite, the most noticeable being the occurrence in the griphite pattern of reflections prohibited by the space group O_h^{10} . Otherwise, it is quite apparent that the more intense lines are those characteristic of garnet. X-ray data must be

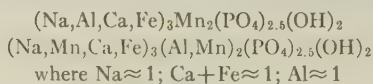
considered with caution when powder diffraction methods are employed to the exclusion of other methods and, particularly, when contamination of the sample is probable. Thus it is not possible to decide the space group of griphite but there is every indication that the structure closely simulates one based upon a body-centered cubic lattice. The true symmetry appears to be lower than that of garnet ($O_h^{10}=Ia\bar{3}d$).

Were it not for several additional factors the conclusion that griphite is a garnetoid might seem unjustifiable. These factors are:

1. The composition indicated by Headden's analysis conforms with the type formula of garnets and garnetoids.
2. The calculated density is virtually identical with the experimental value.
3. The refractive index is similar to what would be expected for a substance with the structure of garnet and the chemical composition of griphite.

CHEMICAL DATA

The mean of Headden's analyses is used as a basis for calculating the cell contents (Table 2), assuming that all of the cations present enter and completely fill the 64 cationic positions of normal garnet and that the lattice contains 96 oxygens. This permits the correlation of griphite and the type formula $X_3Y_2(ZO_4)_3$, or the derived formula $X_3Y_2(ZO_4)_{3-m}(OH)_{4m}$, in one or the other or a combination of the following ways:



Of these possibilities, the former seems more probable, but nothing definite can be decided without a detailed structural investigation. The x-ray and chemical data available at present are not sufficiently complete for this purpose and several factors impede more accurate determinations.

The density calculated from the molecular weight (8×474.5) and the cell edge (12.26 Å) is 3.399. This compares most favorably with the density determined by Headden (3.401) which was confirmed by the writer as 3.40.

The calculations of the cell contents and density have been based on the assumption that all cationic positions of the lattice are filled, but the simultaneous assumption of 96 oxygen positions yields a slight discrepancy between the positive and negative charges. This is not serious, however, and probably is to be explained by the presence of one or more of the impurities mentioned below. An alternate explanation can be obtained by assuming that there are vacancies in the lattice. If it is assumed

TABLE 2. CHEMICAL ANALYSIS AND CELL CONTENTS OF GRIPHITE

Oxides*	Weight per cents	Molecular ratios	Ionic ratios	Contents of $\frac{1}{8}$ unit cell	
				Positive ions	Weights of ions
Li ₂ O	trace	—			
Na ₂ O	5.52	.089	.178	.86	19.8
K ₂ O	0.30	.003	.006	.03	1.1
CaO	7.47	.133	.133	.64	25.7
MgO	0.15	.004	.004	.02	0.5
FeO	4.00	.056	.056	.27	15.1
MnO	29.64	.418	.418	2.02	110.9
Al ₂ O ₃	10.13	.099	.198	.96	25.9
P ₂ O ₅	38.52	.271	.542	2.62	81.2
Cl	0.11	.003			
F	trace	—			
H ₂ O	4.29	.238	4×.119	4×0.58†	2.3
Insol.	0.16	—		12 oxygens	192.0
	100.29			8.00	474.5

* W. P. Headden, analyst. Mean of 2 complete and 3 partial analyses.

† Since $\text{SiO}_2 \rightleftharpoons 2\text{H}_2\text{O}$, the sum of all positive ions should be 8 when 4H are considered equivalent to Si, provided no vacancies occur.

that $\frac{1}{8}$ unit cell has 24 negative charges (12 oxygens) and the cationic charges are balanced in their proper ratios, 7.64 cations are indicated rather than 8. There is no good reason for assuming vacancies in the lattice, however, and it is fully as reasonable to believe that the ratios of the cations would be slightly modified by deduction of impurities, if these could be determined quantitatively.

Spectroscopic observations failed to indicate the presence of prominent lines of Si, As or V in the range 2250–3600 Å, indicating that these elements are not more abundant than traces. With the possible exception of CC₂, Headden's analysis seems to be complete and little improvement could be expected in terms of a new analysis because it is not feasible to separate the minor impurities mentioned below.

ASSOCIATED MINERALS

Griphite resembles most garnets in the number and diversity of the included minerals. The following substances were observed as inclusions:

Hausmannite (?)—Deep red-brown to opaque in thin section. Some of the diffraction lines (Table 1) correspond with the more intense lines of hausmannite.

Pseudowavellite—Colorless; uniaxial (+); $\epsilon > n$ of griphite, $\omega \approx n$ of griphite; medium-low birefringence. Identification made certain by microchemical tests and comparison of x-ray pattern made from concentrated material with patterns of pseudowavellite from Fairfield, Utah, and from Bavaria (U.S.N.M. No. R4271).

Apatite or mangan-apatite (?)—Colorless; low relief in griphite; low birefringence; uniaxial (—). Similar material occurs as spherulites. Possibly accounts for F and/or Cl of Headden's analysis. Identified by optical methods only.

Quartz (?)—Colorless; high negative relief in griphite; low birefringence; uniaxial (+). Identified by optical methods only.

Amblygonite or montebrasite (?)—Colorless; low negative relief in griphite; moderate birefringence; occasionally with polysynthetic twinning. Possibly accounts for Li_2O reported in Headden's analysis. Identified by optical methods only.

All of these minerals are present in very small amounts except hausmannite which is frequently abundant. Two other substances occur as traces but these could not be identified. Diffraction lines of the identified substances, except hausmannite, were not found on the patterns prepared from selected samples of griphite.

In addition to the minerals occurring as inclusions, two specimens furnished by Dr. John C. Haff show considerable amounts of albite, quartz, and a white mica in association with the griphite. One of the unidentified substances occurring as inclusions resembles mica although its identification could not be confirmed.

It is noticeable that three of the contaminating substances are phosphates of one or more of the principal cations of griphite, and this suggests that the cationic ratios of Headden's analysis cannot be strictly representative of griphite. However, there is every reason to believe that they very closely approach the true ratios because the impurities apparently occur in very small amounts, if considerable care is taken to exclude the dark-colored material containing hausmannite. Headden's samples probably did not contain more than a few per cent of this material because they were carefully selected in this respect.

DISCUSSION

The x-ray, chemical, physical, and optical data for griphite are all contributory to the conclusion that this mineral has a structure similar to that of garnets. There seem to be no theoretical objections to this and, consequently, griphite has been classified as one of the garnetoids. The properties of the garnetoids are summarized in Table 3.

The occurrence of isomorphous mixtures of the Ca-Fe- and Ca-Al-hydrogarnets with corresponding true garnets has been shown (3); plazolite (7) represents such an intermediate isomorphous compound. Manganese- and magnesium-berzeliite probably form a complete series of isomorphous mixtures but these "molecules" are not known to occur

TABLE 3. SUMMARY OF THE PROPERTIES OF GARNETOIDS

	Composition	n	G	H	F	Solubility	Cell edge
Griphite	(Na, Al, Ca, Fe) ₃ Mn ₂ (PO ₄) _{2.5} (OH) ₂	1.64-1.66	3.40	5½ ^a	easy ^a	sol. HCl	12.26 Å
Plazolite	Ca ₃ Al ₂ (SiO ₄) ₂ (OH) ₄	1.675 ^b	3.13 ^c	6½ ^b	fusible ^d	sol. HCl ^b	12.14 ^e
Ca-Al-hydrogarnet*	Ca ₃ Al ₂ (OH) ₁₂	1.605 ^e	2.52 ^f	—	—	—	12.56 ^g
Sr-Al-hydrogarnet*	Sr ₃ Al ₂ (OH) ₁₂	—	3.12 ^g	—	—	—	13.02 ^h
Ca-Fe-hydrogarnet*	Ca ₃ Fe ₂ (OH) ₁₂	1.710 ^e	2.78 ^g	—	—	—	12.74 ^e
Mn-berzeliite	(Ca ₂ Na)Mn ₂ (AsO ₄) ₃	1.78 ^j	4.45 ^j	5j	3j	sol. acid	12.46 ^k
Mg-berzeliite	(Ca ₂ Na)Mg ₂ (AsO ₄) ₃	1.71 ^j	3.95 ^j	5j	3j	sol. acid	12.35 ^k

* Compounds produced by synthesis, not known to occur naturally.

^a W. P. HEADEN: *op. cit.* ^b W. F. FOSHAG: *op. cit.* ^c A. PABST: *op. cit.*^d A. PABST: *Minerals of California*, p. 294. ^e E. P. FLINT, H. F. McMURDIE and L. S. WELLS: *op. cit.* ^f T. THORVALDSON, N. S. GRACE and V. A. VIGFUSSON: *Canadian Jour. Research*, **1**, 201 (1929). ^g Calculated from cell edge. ^h E. BRANDENBERGER: *Schweiz. mineral. petrogr. Mitt.*, **13**, 570 (1933). ⁱ E. S. LARSEN and H. BERMAN: *U.S.G.S. Bull.* **848** (1934). ^k W. BUBECK and F. MACHATSKHI: *op. cit.*

isomorphously mixed with any other garnetoid or garnet. Nothing is known regarding the miscibility of griphite with garnets and other garnetoids. However, analyses of garnets occasionally indicate the presence of small amounts of Na_2O and, rarely, very small amounts of P_2O_5 .

A similar compound, originally described as triplite but later referred to griphite, from near Rapid City, South Dakota, was analyzed by L. G. Eakins (8). The analysis shows a slightly higher value for P_2O_5 , slightly less water, considerably more fluorine and 2.36 per cent of Fe_2O_3 . In general, however, this analysis is conformable with Headden's results and confirms the composition assigned to griphite.

Eakins' analysis reports about $\frac{1}{4}$ of 1 per cent of CO_2 . The fact that specimens studied in the present investigation were observed to liberate gas when treated with acid suggests that a small amount of CO_2 was overlooked by Headden.

Carbon dioxide is known to enter the lattice of apatite (9) and there is no theoretical reason which prohibits its occurrence in the structure of griphite. In the present investigation observations made with the microscope revealed the liberation of gas during treatment with dilute H_2SO_4 from portions of the griphite that were completely isotropic. It can be said with certainty that neither calcite nor aragonite was present.

SUMMARY

Griphite is cubic and its structure is similar to that of garnets, i.e., it closely simulates a structure based on a body-centered cubic lattice, although the true symmetry is probably lower than that of garnets.

The structural formula of griphite is $8[(\text{Na}, \text{Al}, \text{Ca}, \text{Fe})_3\text{Mn}_2(\text{PO}_4)_{2.5}(\text{OH})_2]$, which correlates with the type formula $\text{X}_3\text{Y}_2(\text{ZO}_4)_{3-m}(\text{OH})_{4m}$, the latter being a variation of the formula $\text{X}_3\text{Y}_2(\text{ZO}_4)_3$.

The properties of the garnetoids (substances other than simple silicates having a structure similar to garnets) have been assembled and compared.

Pseudowavellite is reported from a second American locality. Its identification was confirmed by x -ray and microchemical methods.

Schorlomite is classified as a true garnet rather than a garnetoid because the substitution encountered here does not produce any significant changes in the powder diffraction pattern. Lattice dimensions are given for schorlomite (12.09 Å) and for uvarovite (11.97 Å) in addition to griphite (12.26 Å).

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anticathode was provided by a grant-in-aid by the society of Sigma Xi.

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I am indebted to my associates, Mr. Roger Rhoades and Drs. W. H. Irwin and R. C. Mielenz for helpful suggestions. Mr. J. L. Gilliland prepared the spectroscopic plates used in the qualitative detection of Si, As, and V, and assisted in other ways. Drs. A. Pabst, R. B. Ellestad, J. W. Gruner, and J. C. Haff read the manuscript and furnished valuable comments.

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NOTES AND NEWS

PLEONASTE FROM MINERAL COUNTY, NEVADA

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As pleonaste, the iron-magnesia spinel, has not previously been found in Nevada, other than in microscopic crystals in thin sections, a description of recently discovered large masses of this mineral should be of interest. This spinel was first brought to my attention, early in 1940, through specimens sent in for determination.¹ This material was found by prospectors working in the Garfield Hills, one and a half miles southwest of Kinkead siding. Kinkead siding is on the Hazen branch of the Southern Pacific railroad and is eleven miles east of Hawthorne on U. S. Highway 95.

A visit was made to the region, specimens collected, and a brief study made of the area. The principal rocks of the region are a series of limestones, probably dolomitic, which have been intruded by a granitic rock. Small irregular masses of the intrusive were seen at several places within the sedimentary rocks. No detailed study was made of the areal geology but, from the lithology of the formations and reference to the excellent work of Muller and Ferguson in this area,² there can be little doubt that the limestones are a part of their Luning formation of Upper Triassic age. In the vicinity of the contact characteristic pyrometamorphic minerals have been developed in the limestone with the formation of garnet, light to dark green epidote, idocrase, zoisite, and other lime silicates. The idocrase occurs in light brownish-yellow crystals, some of which are well-formed and as much as three fourths of an inch in length. Copper mineralization is present near the contact and mining on a small scale was carried on there many years ago. At these copper prospects there is a considerable amount of chrysocolla and minor quantities of malachite, azurite, and other oxide copper minerals.

The spinel-bearing area is about a half mile east of the copper prospects. At this place the sediments strike approximately east and west and stand nearly vertical. The pleonaste, dark green to nearly black in color, is present in roughly lenticular masses up to two feet wide and fifty or more feet long. These masses are parallel to the strike of the sediments and extend for a distance of several hundred feet. These masses appear to favor a certain horizon although smaller masses are found in adjacent beds. As only a small area was seen during the study of the spinel-bearing

¹ The pleonaste was identified by the Nevada State Analytical Laboratory.

² Muller, S. W., and Ferguson, H. G., Mesozoic stratigraphy of the Hawthorne and Tonopah quadrangles, Nevada: *Geol. Soc. Amer., Bull.* **150**, 1573-1624 (1939).

ing limestone it is altogether probable that the pleonaste is much more widely distributed than is known at present. Pleonaste occurs in rather pure crystalline masses and is also intergrown with calcite and other minerals. Usually the pleonaste occurs in finely-granular aggregates with occasional octahedra. Some specimens reveal well-formed octahedra, some of which may be four, or more, centimeters in length.

A sample was prepared for analysis by carefully crushing some of the better material and screening out the fines. A treatment with dilute hydrochloric acid removed the calcite, and other impurities were then removed by careful sorting under a binocular microscope. Further separation was accomplished through the use of a heavy liquid. The final sample was quite pure. The specific gravity (3.530) was determined by the pycnometer method and the index of refraction ($1.725 \pm .002$) by comparison with index liquids.

ANALYSIS OF PLEONASTE

	(1) ^a	(2)
	%	%
SiO ₂	2.05	
Al ₂ O ₃	66.86	67.93
Fe ₂ O ₃	5.72	5.81
Cr ₂ O ₃	none	
FeO	2.01	2.04
CaO	none	
	<hr/> 100.47	<hr/> 100.00

^a Average of two concordant analyses.

1. Analysis of pleonaste by Wilbur G. Hedquist.

2. Analysis recalculated to 100%, considering the silica as an impurity.

I wish to acknowledge my appreciation of the work of Mr. Wilbur G. Hedquist who prepared the sample and ran the analyses and also aided in the determination of the specific gravity.

FULL FIELD VIEW OF INTERFERENCE FIGURES

F. H. GOLDMAN

Ordinarily it is not always possible to obtain clear interference figures which will occupy the full field when employing a polarizing microscope such as the Spencer #37. To do so would necessitate either raising the condenser above the stage (this is the combined condenser N. A. 1.40 and N. A. 1.0) or moving the lamp directly under the polarizer. It was found that the equivalent result was obtained with not too great loss of light by inserting a ground glass disc, or plate, directly below the polarizer. In the Spencer #37 there is provided a slot which will accommodate such a disc very nicely.

Such a ground glass plate will also eliminate the central bright spot of light obtained when using a very low-power objective such as a 40 mm. 2.8 \times without the necessity of removing the condenser.

MATERIAL DESIRED

We are undertaking, with G.S.A. help, a re-study of plagioclases in order to obtain more complete data. We are finding difficulty in obtaining an adequate variety of material even after exhausting our own field supplies collected for the purpose and all promising samples from various catalogues. We have received generous help and offers of help after the announcement of the G.S.A. grants.

It occurs to us that the interest in more reliable plagioclase data is wide enough that others may be willing to send us samples on hand or be good enough to collect some for the purpose in the coming field season. We have funds to pay only the freight charges at this end.

Our needs are: rock carrying plagioclase of *any* composition but especially between 0-20% anorthite and between 80-100% anorthite. We are concentrating our efforts on routine rocks though pegmatites are acceptable. We are not using altered plagioclase or any with more than a minimum of inclusions. We should have some information about the nature of the occurrence—preferably a statement which we may quote. The size of the sample depends on the per cent of suitable plagioclase present, and ordinarily ranges from 5-10 pounds for pegmatites to 15-20 pounds for a volcanic rock in which the phenocrysts are sought. Any fresh plagioclase-bearing rock in which the plagioclase grain size is 2 mm. or more is suitable. We shall genuinely appreciate specimen contributions. They may be addressed to one of us, freight collect, at Science Hall, Madison, Wisconsin. Freight offices are instructed not to accept "valueless" articles collect. We will send by return mail a guarantee of payment of freight charges at this end, which guarantee we are assured will be accepted in lieu of pre-payment. Please do not make shipments by express.

R. C. Emmons

Robert M. Gates

Edmund Clabaugh

PROFESSOR ARTHUR F. BUDDINGTON, chairman of the Geology Department of Princeton University and currently President of the Mineralogical Society of America, was the recipient of the honorary degree of Doctor of Science at the 174th annual commencement of Brown University, May 18, 1942.

PROCEEDINGS OF SOCIETIES

A joint meeting of the American Association for the Advancement of Science, Section C, and the American Society for X-Ray and Electron Diffraction will be held at Gibson Island, Maryland, July 27-31, 1942. Registration and reservations are made only through the Director of the Gibson Island Conferences, Prof. Neil E. Gordon, Central College Fayette, Missouri. The present program is as follows:

X-RAY AND ELECTRON DIFFRACTION

B. E. Warren, *Chairman*

A. L. Patterson, *Vice-Chairman*

July 27

- | | |
|--------------|------------------------------------------------------------|
| I. Fankuchen | X-Ray Patterns of Imperfect Crystals |
| J. T. Norton | X-Ray Diffraction Methods for Measuring Stresses in Metals |

July 28

- | | |
|-------------------|----------------------------------------------------|
| J. C. M. Brentano | Intensities in X-Ray Diffraction |
| K. Lark-Horovitz | Intensity Problem in Electron Diffraction Patterns |

July 29

- | | |
|-----------------|---------------------------------------------------------------------|
| S. B. Hendricks | Types and Extent of Isomorphous Replacements in Silicate Structures |
| P. Debye | Temperature Diffuse Scattering |

July 30

- | | |
|----------------|-----------------------------------------------------------------------------|
| L. K. Frevel | Chemical Analysis by Diffraction Methods |
| W. O. Milligan | X-Ray and Electron Diffraction Examination of Inorganic Colloidal Materials |

July 31

- | | |
|-----------|-----------------------------------------------------|
| D. Harker | Metallographic Results with the Electron Microscope |
|-----------|-----------------------------------------------------|

A business meeting of the American Society for X-Ray and Electron Diffraction will be held at the Gibson Island Conference Room, Wednesday afternoon, July 29, 1942.

NEW MINERAL NAMES

Royite

N. L. SHARMA: Royite, a new variety of quartz, from the Jharia coal-field. *Proc. Indian Acad. Sciences*, **12B**, 215-220 (1940).

NAME: For Professor S. K. Roy, Indian School of Mines.

CHEMICAL PROPERTIES: Analysis by S. C. Niyogy gave SiO_2 95.78, MgO 2.04, Al_2O_3 1.80, Fe_2O_3 0.14, CaO 0.37, MnO 0.03, TiO_2 trace; sum 100.16. The sample contained limonite and biotite along cracks.

PHYSICAL AND CHEMICAL PROPERTIES: Color, brownish-black to black. Streak, colorless. $G = 2.65$. $H = 7$. Optically uniaxial, positive; the refractive indices are stated to agree with those of quartz. Shows undulatory extinction with $Z/\angle c$ variable, 0 to 5° . Differs from ordinary quartz in having a good prismatic cleavage and also a transverse cleavage which makes the crystals break into rhomb-like forms. Cleavage surfaces show a characteristic schiller luster.

OCCURRENCE: Found at various localities in the Jharia coal-field, usually along joint planes of sandstones and shales.

DISCUSSION: The custom of adding to the mineralogical literature new names based on trifling variations in habit or physical properties has tended to die out in recent years. Unfortunately, as the present example shows, it has not yet become extinct.

M. F.

DISCREDITED MINERALS

Stibiomicrolite

OLOF H. ÖDMAN: On "stibiomicrolite" and its decomposition products. *Geol. Fören. Förhandl.* (Stockholm) **63**, 289 (1941). Material from the Varuträsk pegmatite was described by Quensel and Berggren, abstract in *Am. Mineral.*, **23**, 542 (1938), as being a mixture of stibiotantalite and microlite, plus minor amounts of native antimony and senarmontite. It was then supposed that the mixture was the result of exsolution from a homogeneous phase, and the name stibiomicrolite was proposed for the original mineral. Ödman now shows by optical study that the stibiotantalite was the primary mineral, the others being hydrothermal alteration products of it. The name stibiomicrolite should be dropped.

M. F.

Ainalite, Ixiolite

KARIN ÅMARK: An x-ray study of stanniferous columbite from Varuträsk and of the related Finnish minerals ainalite and ixiolite. *Geol. Fören. Förhandl.* (Stockholm) **63**, 295 (1941).

PERCY QUENSEL: Cassiterite and stanniferous columbite. *Ibid.*, **63**, 300 (1941).

Ainalite was described in 1863 as a cassiterite containing 8.78% Ta_2O_5 . Ixiolite was described in 1857 as an orthorhombic tantalite containing up to 12.8% SnO_2 . From x-ray and optical studies of the natural minerals and of some synthetic mixtures, it is concluded that the mutual miscibility of SnO_2 and either the orthorhombic or tetragonal tantalate-columbates (tantalite, tapiolite) is, at most, very slight. The minerals are mechanical mixtures. Both names should be dropped. The name ixiolite has also been used (Simpson, 1909) for tetragonal $MnTa_2O_6$ (tapiolite group). This usage should also be dropped, since it does not conform to the original definition.

DISCUSSION: A. B. Edwards, *Australasian Inst. Mining and Metallurgy*, no. 120, p. 731 (1940), has examined optically a number of Australian samples similar to those from Sweden and Finland. A sample of tantalite containing 0.4% SnO_2 and one of mossaite containing 4.5% SnO_2 , both contained visible cassiterite, but another sample of tantalite with 1.5% SnO_2 showed no cassiterite. Two samples of cassiterite contained 3.86 and 17.5%, respectively, of $Ta_2O_5 + Cb_2O_5$. A second phase (tantalite or tapiolite) was present in both samples, but there was about the same amount of tapiolite (?) present in the two samples. Edwards believes that cassiterite and tapiolite form solid solutions at high temperatures, which unmix completely, or nearly completely, on cooling.

M. F.